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An Application of Statistical Methods to Compare the Properties of Concretes Produced from Construction Waste

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1. Introduction and aim

Some waste substances, although not directly aggressive towards the environment, cause an increase in the overall amount of matter sent to landfills when not rationally recycled. The group includes construction ceramic materials (bricks, breeze blocks, roof tiles, pipes, wall and floor tiles, taps, sinks, bathroom furnishings, elements of electric wiring and sanitation facilities) (Ciechocki et al. 2014, Halicka et al. 2013). Taking the above facts into account, efficient ways of recycling of the aforementioned materials are sought (Motz & Geisler 2001, Yang et al., 2011). Concrete production is one of recycling methods for construction ceramic products or waste generated during their production (Domski & Głodkowska 2017, Ogrodnik et al. 2017). Their use in concrete mixtures does not require special treatment as they are used as aggregates following crushing in conventional crushing machines widely used in production plants. Concretes made with construction ceramics have different physical, chemical and mechanical properties compared with conventional concretes. The composition of various concrete mixes is altered by selection of cement, aggregate and additives or admixtures. Concretes which gain unique properties are called special concretes and they can be water-resistant, frost-resistant, corrosion-resistant (acidproof, sulphate-resistant); there are also concretes for radiation shielding and insulation concretes (Guerra et al. 2009, Ogrodnik et al. 2012). The array of special concretes has expanded recently to include concretes solely made with recycled aggregates. Demand for environmentally-friendly products is constantly on the increase, which has been confirmed in numerous studies in which concrete production involved using different recycled materials e.g. construction waste (De Brito et al. 2005, Domski et al. 2012, Dowrzańczyk-Krzywiec 2011, Zając 2008), remains of concrete mixture (Gawęda et al. 2013, Gruszczyński 2017), industrial concrete floors and reinforced concrete beams (Węgliński et al. 2017). Usually, concretes made with recycled materials are compared to conventional products in terms of their physical and chemical properties. However, rarely are they compared by means of statistical methods (Gawenda et al. 2005). Thus, the aim of the present work was to carry out statistical analysis and examine variation in properties of concretes with altered composition, compared with conventional concretes. The work is the continuation of the previous research by Zegardło et al. (2018).

2. Materials and methods

The research material consisted of ceramic waste deposited in the building material landfills: red ceramics (mainly crushed bricks, ceramic building blocks, shards of roof tiles), ceramic tiles and sanitary ceramics. The waste materials were crushed using jaw crushers to obtain fine and coarse aggregates (the size of aggregate particles was respectively, 0-4 and 4-8 mm). In order to establish an optimum coarse-to-fine aggregate particle ratio, mixtures of aggregate particles were placed in vessels whose diameter was 1.69 dm^3. The proportions were establish so that the spaces between coarse particles were completely filled with finer particles. In the present research, the coarse-to-fine particle ratio was 1:0.4. Next, using the optimised proportion (1:0.4), mixtures of aggregates of sanitary ceramics, tile ceramics and red ceramics were prepared, and their percentage particle content was determined in accordance with PN-EN 933-1:2012. Moreover, specific density, apparent density, water absorbability and crushing rate were determined for each aggregate type. In order to establish specific density, a standard method was used in accordance with PN-EN1097-7. To that end, aggregates were ground to obtain dust, dried until constant weight was reached, and weighed. The volume of aggregate portions was measured by the pycnometric method. Bulk density and water absorbability were determined by the standard method in accordance with PN-EN 1097-6. Measurements were taken in 10 samples.

Water absorbability of aggregate was expressed as percentage weight of water absorbed by the aggregate to the aggregate dry weight. Aggregate bulk density was the ratio of aggregate weight to aggregate volume. Determination of elemental composition was the final analysis.

The obtained aggregates were used to make concrete samples in which all conventional aggregates were replaced with recycled ceramic tiles, red ceramics and sanitary ceramic aggregates (10 samples of each type). Additionally, for the sake of comparison, samples of standard concretes (gravel- and basalt-based) were prepared using the same proportions of the remaining components (excluding aggregates).

Next, the following concrete properties were determined: tensile strength, compressive strength and compressive strength in a corrosive environment.

In order to statistically compare aggregates (in terms of crushing rate, bulk density, specific density, water absorbability) and concretes (in terms of tensile strength, compressive strength, compressive strength in a corrosive environment, and Al_2O_3 and SiO_2 contents), one-way analysis of variance (ANOVA) was used following the model:

$$y_{ij} = m + a_i + e_{ijl} \tag{1}$$

where:
y_{ij} – value of the examined characteristic,
m − population mean,
a_i – effect of i-th level of factor A (aggregate type, concrete type),
e_{ijl} – random error.

Tukey's test was used for mean separation at $p \leq 0.05$.

The relationships between aggregate characteristics, that is specific density, bulk density, water absorbability and crushing rate, were examined by means of Pearson's correlation coefficient.

As analysis of variance makes it possible to perform multi-trait comparisons but the traits are considered separately, principal component analysis (PCA) and cluster analysis were used because they allow simultaneous comparisons in terms of many characteristics.

As variance analysis makes it possible to compare objects in terms of many characteristics which are viewed separately, principal component analysis (PCA) and cluster analysis were applied to simultaneously compare objects (concretes) in terms of many characteristics (tensile strength, compressive strength, compressive strength in a corrosive environment, Al_2O_3 content, SiO_2 content).

Only the principal components whose eigenvalues, according to the Kaiser's criterion, were greater than 1 were analysed and interpreted. The distance between clusters was estimated by Ward method based on Euclidean distance. The cut-off point (level of cluster similarity) was determined using Mojena rule following the inequality:

$$d_{i+1} > \bar{d} + ks_d; \tag{2}$$

where: $\bar{d}$ and s_d are, respectively, the mean and standard deviation of d_i and k is a constant in the range 2.75 to 3.50 (Mojena 1977). The value k was 1.2 as recommended by Milligan and Cooper (1985).

All the calculations were performed using STATISTICA 12.0.

3. Results and discussion

Statistical analysis demonstrated that aggregates from ceramic waste differed significantly in terms of the analysed characteristics (Fig. 1). Variance analysis revealed significant differences between ceramic tile aggregates in terms of crushing rate ($F = 189.1$, $p = 0.000$), specific density ($F = 75.46$, $p = 0.000$) bulk density ($F = 32.51$, $p = 0.000$) and water absorbability ($F = 47.86$, $p = 0.000$) (Fig. 1).

According to Zając and Gołębiowska (2014), properties of recycled aggregates differ significantly according to their origins.

Aggregates from red ceramics were the most crushed following by aggregates from tile ceramics and basalt grit. The crushing rate of tile ceramic aggregates was statistically the same as that of conventional aggregates. According to Gawenda et al. (2013), resistance to crushing is one of the factors which condition ceramic aggregate suitability for concrete production.

The highest specific density and bulk density were determined for aggregates from basalt grit, it being the lowest for aggregates from red ceramics. Aggregates from tile ceramics had a significantly higher specific density and bulk density compared with red ceramics, it being lower compared with aggregates from sanitary and conventional ceramics as well as from basalt grit. No statistical differences between specific density and bulk density of sanitary ceramic aggregates and conventional aggregates were found.. The specific density and bulk density of these aggregates were significantly lower compared with basalt grit but it was higher compared with aggregates produced from sanitary and red ceramics.

Red ceramic aggregate had the highest water absorbability which differed significantly from that of the other aggregates. Water absorbability of tile ceramic aggregate was also significantly higher compared with sanitary ceramic aggregate, conventional aggregate and basalt grit aggregate. The water absorbability of conventional aggregate and that produced form sanitary ceramics was statistically the same. The lowest water absorbability which differed from the remaining aggregates was determined for basalt grit (Fig. 1). Substantial water absorbability of sanitary ceramics, which was similar to the absorbability of limestone and dolomite, was confirmed in the research by Halicka & Zegardło (2011).

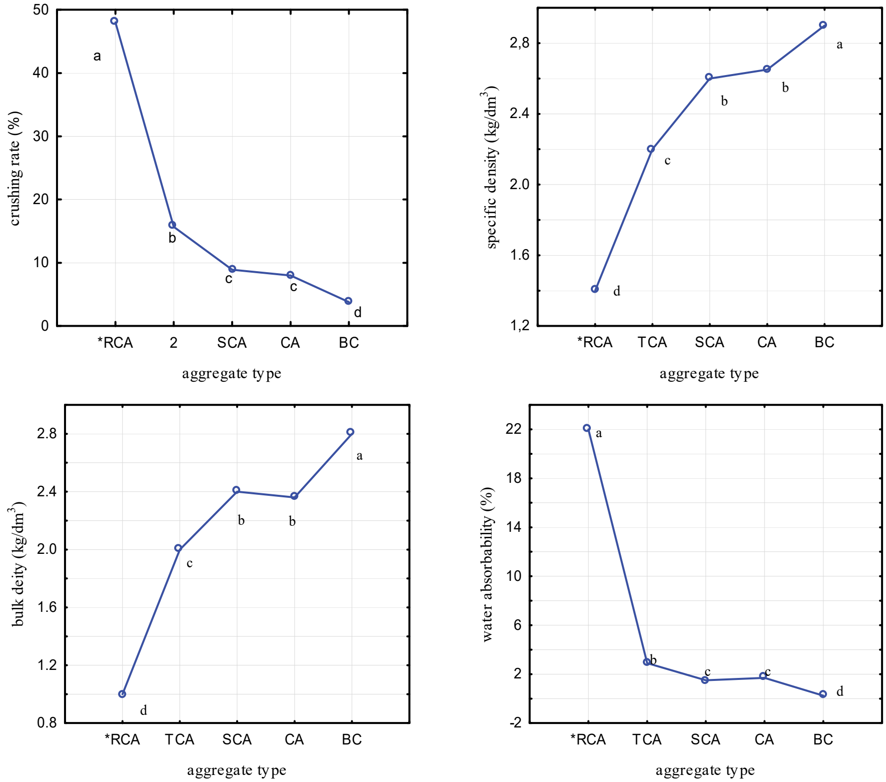

Fig. 1. Comparison of mean values of aggregate properties in terms of the analysed characteristics

Means designated by the same letters differ insignificantly at $p \leq 0.05$.
RCA– Red ceramic aggregate, TCA – Tile ceramic aggregate, SCA – Sanitary ceramic aggregate, CA– Conventional aggregate (gravel), BG – Basalt grit

Correlation analysis revealed a significant positive association between bulk density and specific density of red ceramic aggregate. An increase in specific density was followed by an increase in bulk density ($r = 0.710$). Water absorbability of aggregate from red ceramics declined significantly ($r = -0.807$) as specific density and bulk density increased ($r = -0.753$). Moreover, the more crushed aggregates were, the higher water absorbability was found ($r = 0.724$). Absorbability of aggregate from tile ceramics declined significantly as bulk density increased ($r = -0.719$) and crushing rate dropped ($r = 0.736$). The latter property significantly and positively affected an increase in bulk density ($r = 0.738$) and water absorbability ($r = 0.726$) of aggregate produced from sanitary ceramics. Similar relationships were observed for conventional aggregate, although no relationship between its specific density and crushing rate was confirmed. Water absorbability of basalt grit aggregate declined significantly as specific density and bulk density increased (r = 0.729 and 0.811, respectively). Moreover, the absorbability increased as crushing rate increased (r = 0.778) (Table 1).

Table 1. Values of correlation coefficients between the aggregate properties

Items	Red ceramic aggregate (RCA)			
	Specific density	Bulk density	Water absorbability	Crushing rate
Specific density	1.00	0.710*	-0.807*	0.094
Bulk density		1.00	-0.753*	0.036
Water absorbability			1.00	0.724*
Crushing rate				1.00
	Tile ceramic aggregate (TCA)			
Specific density	1.00	0.135	-0.450	0.189
Bulk density		1.00	-0.719*	0.395
Water absorbability			1.00	0.736*
Crushing rate				1.00
	Sanitary ceramic aggregate (SCA)			
Specific density	1.00	0.276	-0.136	0.738*
Bulk density		1.00	-0.605	0.222
Water absorbability			1.00	0.726*
Crushing rate				1.00
	Conventional aggregate (gravel) (CA)			
Specific density	1.00	0.424	-0.606	0.169
Bulk density		1.00	-0.738*	0.369
Water absorbability			1.00	0.802*
Crushing rate				1.00
	Basalt grit (BG)			
Specific density	1.00	0.236	-0.729*	0.089
Bulk density		1.00	-0.811*	0.369
Water absorbability			1.00	0.778*
Crushing rate				1.00

Statistical analysis of concrete strength demonstrated significant differences between the concretes. The highest values of strength parameters were obtained for concrete produced using aggregate from sanitary ceramics. Conventional aggregate replaced with aggregates from tile ceramics and basalt grit significantly increased compressive strength and tensile strength of the remaining concretes. Concrete made with aggregate from red ceramics had significantly lower values of compressive strength and tensile strength compared with concretes made with the remaining types of aggregates (Fig. 2).

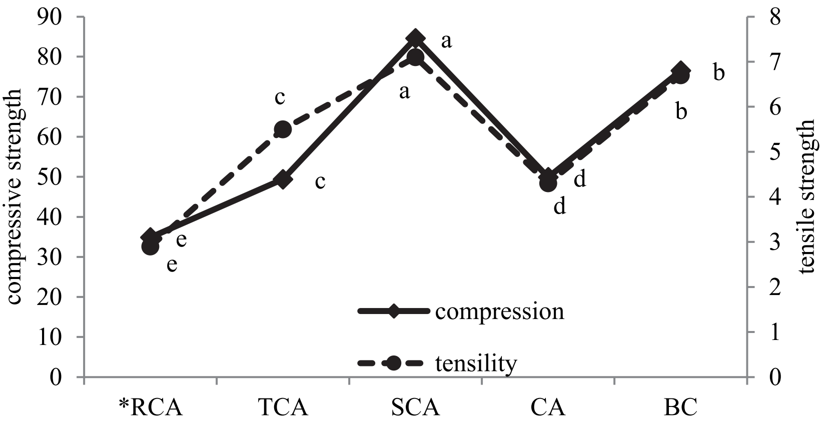

Fig. 2. Mean values of concrete strength
Means designated by the same letters differ insignificantly at $p \leq 0.05$.
RCA – Red ceramic aggregate, TCA – Tile ceramic aggregate, SCA – Sanitary ceramic aggregate, CA – Conventional aggregate (gravel), BG – Basalt grit

As can be seen in Figure 3, concretes containing basalt grit and tile ceramics had the highest silica content, it being significantly higher compared with concretes made with conventional aggregate and that produced from red ceramics. The silica content of concrete containing sanitary ceramics was similar to conventional concrete as well as concrete including tile ceramics. The greatest resistance to a corrosive environment was displayed by concrete made with tile ceramics, the resistance being significantly higher compared with the remaining concretes. The lowest values of the discussed parameter were determined for concrete made with conventional aggregate and aggregate from red ceramics, the differences between these two types being insignificant.

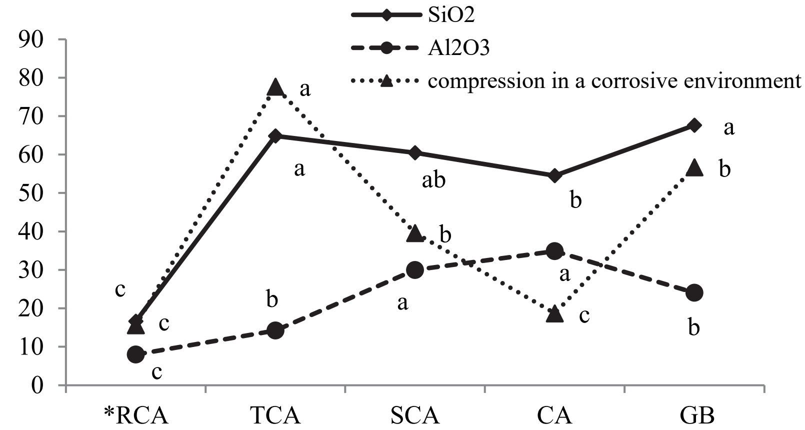

Fig. 3. Mean values of concrete compressive strength in a corrosive environment
Means designated by the same letters differ insignificantly at $p \leq 0.05$.
RCA– Red ceramic aggregate, TCA – Tile ceramic aggregate, SCA – Sanitary ceramic aggregate, CA– Conventional aggregate (gravel), BG – Basalt grit

Due to the fact that analysis of variance makes it possible to compare objects in terms of many characteristics but they are considered separately, principal component analysis and cluster analysis were used to obtain simultaneous multi-trait comparisons of concretes in terms of all the analysed characteristics. Principal component analysis revealed that properties of concretes made with various aggregates had different characteristics associated with the first two principal components (PC1 and PC2), as indicated by their eigenvalues which are higher than 1. The components accounted for over 86% of multi-trait variation between the concretes (Table 2). The first principal component was positively correlated with tensile strength (0.928), silica content (0.894) and compressive strength (0.878). The following characteristics were the most strongly associated with the second principal component: compressive strength in a corrosive environment (-0.712) and Al_2O_3 content. Multi-trait relationships indicate that the concretes which contained more silica had a higher compressive strength, tensile strength as well as compressive strength in a corrosive environment. The association of silica content with compressive strength and tensile strength was quite strong as indicated by a small inclination angle between the variables. Such an effect may result from chemical reactions between SiO_2 and concrete components. Silica reactions between aggregate and concrete improve the properties of the aggregate-set cement contact point, which positively influences the final strength parameters of the composites. Concretes which contained more Al_2O_3 had lower compressive strength in a corrosive environment as demonstrated by the reciprocal location of the vectors (Fig. 4).

Table 2. Eigenvalues, share of principal components in the overall variation and correlation coefficients between the components and concrete parameters

Specification	Principal components	
	PC1	PC2
Tensile strength	0.928	0.103
Compressive strength	0.878	-0.054
Compressive strength in a corrosive environment	0.646	-0.712
Al_2O_3 content	0.524	0.811
SiO_2 content	0.894	-0.015
Eigenvalue	3.12	1.17
Cumulated variance (%)	62.54	86.13

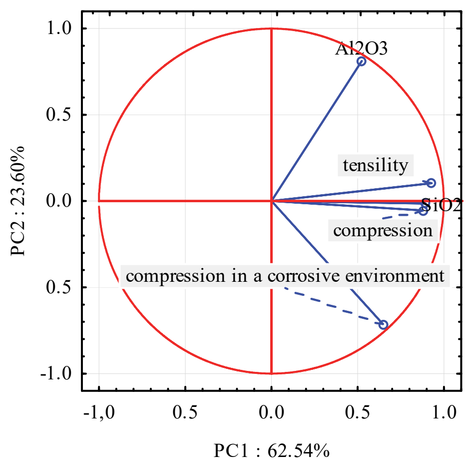

Fig. 4. Graph of factor coordinates for the components PC1 and PC2

The location of concrete types in the system of the first two principal components is presented in Fig. 5. The distance between the objects (concretes) approximately reflects the multi-trait similarity between them in terms of the five analysed characteristics. It can be inferred from the graph that there was a poor multi-trait similarity between the concretes, the most similar being the concretes produced using basalt grit and tile ceramics. The concretes were characterised by average values of traits associated with the first principal component (silica content as well as compressive strength and tensile strength) as the values for this component fluctuated around zero. Concrete made with red ceramics had high negative values of the first principal component so its silica content, compressive strength and tensile strength were low. Concrete whose component were sanitary ceramic aggregates contained more silica and its compressive strength and tensile strength were higher compared with concrete based on aggregates of basalt grit and tile ceramics as well as conventional concrete. The relationships were confirmed by cluster analysis which yielded three groups of concretes classified based on all the analysed characteristics (Fig. 6). The first group was made up of concretes made with tile ceramics, basalt grit and conventional aggregates. The second group included concrete made with sanitary ceramics only, and the third group consisted of concrete containing red ceramic aggregate. The agglomeration course indicated that, in terms of all the analysed characteristics, concrete including tile ceramic aggregate and basalt grit aggregate had the most similar properties as they formed a cluster at the first step. At the second step, concrete produced from conventional aggregates joined the first cluster. At the third and fourth step, group two and three were formed as a result of agglomeration (table 3.)

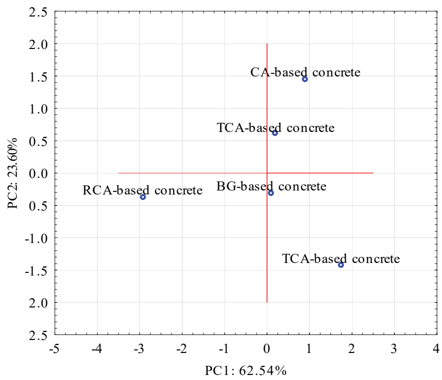

Fig. 5. Location of concrete types in the system of the first two components

Table 3. Agglomeration schedule (clustering) of concretes

Step	Concrete type				
1	TCA-based	BG-based			
2	TCA-based	GBA-based	CA-based		
3	SCA-based	TCA-based	GBA-based	CA-based	
4	RCA-based	SCA-based	TCA-based	GBA-ba	CA-based

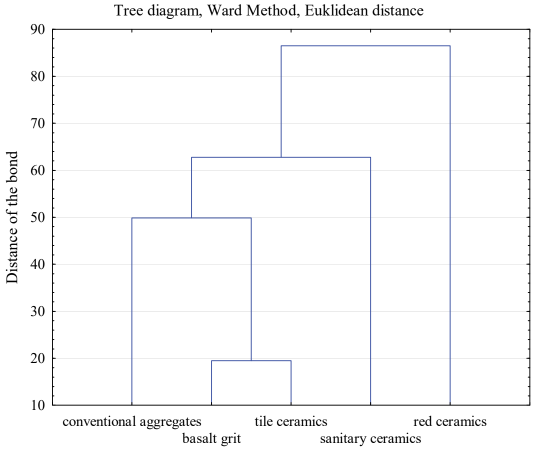

Fig. 6. Dendrogram of division of concretes

4. Summary

Having joined the European Union, Poland has committed herself to comply with European directives concerning a systematic increase in the amount of recycled waste. The present-day state of technology makes it possible to process various forms of unwanted matter into recycled raw materials. However, there are many substances whose storage, although non-aggressive towards the environment, increases the quantity of produced waste. Such substances include ceramics which cannot be bio-reprocessed and, due to growing demand for ceramic products, the amount of this type of waste is on the increase. As a result, attempts are made to search for rational ways of their use. Utilisation of building waste includes production of concrete made with aggregates from these materials. The present research, involving an application of statistical methods, demonstrated that aggregates of building waste materials of sanitary ceramics are suitable for use as aggregate for concrete production, the concrete having superior strength parameters compared with concrete produced using conventional aggregate. The poorest concrete quality parameters were obtained when conventional aggregate was replaced with red ceramic aggregate. Parameters of concretes produced using tile ceramics and sanitary ceramics demonstrated that the aggregates can be a substitute of gravel aggregate. Utilisation of recycled aggregate for concrete production may contribute to reduction in the amount of stored waste materials and reduction in demand for natural aggregate.

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Abstract

The work presents statistical analysis and comparison of quality parameters of concretes produced using conventional and recycled aggregates. The analysis is the continuation of the authors' previous research. The following properties of aggregates were tested: bulk density, specific density, water absorbability, crushing rate, and concrete properties such as compressive strength and tensile strength as well as compressive strength in a corrosive environment. There were determined statistical differences between the characteristics for all the aggregate and concrete types. The analysis demonstrated that concrete containing red ceramics had significantly the lowest values of compressive strength and tensile strength. Use of sanitary and tile ceramics significantly improved concrete properties. Cluster analysis revealed that concretes containing conventional aggregates (gravel and basalt grit) and tile ceramics were the most similar in terms of all the characteristics (compressive strength, tensile strength, compressive strength in a corrosive environment and Al_2O_3 and SiO_2 contents).

Key words:
sanitary ceramics, quality parameters, recycled substance, principal component analysis, cluster analysis

Wykorzystanie metod statystycznych do porównania właściwości betonów wytworzonych z odpadów budowlanych

Streszczenie

W pracy przedstawiano statystyczną analizę i porównanie parametrów jakościowych betonów wytworzonych z udziałem kruszyw tradycyjnych i recyklingowych. Analiza ta jest kontynuacją wcześniejszych badań własnych. Analizie statystycznej zostały poddane cechy kruszyw (gęstość objętościową, gęstość właściwa, nasiąkliwość i współczynnik rozkruszenia) oraz cechy betonów (odporność na ściskanie i rozciąganie oraz ściskanie w środowisku korozyjnym). Określono statystyczne różnice pomiędzy cechami dla wszystkich rodzajów kruszyw i betonów. Analiza wykazała, że beton do produkcji którego użyto ceramiki czerwonej odznaczał się istotnie niższymi wartościami odporności na ściskanie i rozciąganie. Zastosowanie ceramiki sanitarnej i glazurniczej w istotny sposób polepszyło właściwości betonów z tych kruszyw. Na podstawie analizy skupień ustalono, że pod względem wszystkich cech (wytrzymałości na ściskanie, rozciąganie, ściskanie w środowisku korozyjnym, zawartości Al_2O_3 i SiO_2) najbardziej podobne okazały się betony oparte na kruszywach tradycyjnych (żwirowym i bazaltowym) i ceramice glazurniczej

Słowa kluczowe:
ceramika sanitarna, parametry jakościowe, substancja recyklingowa,
analiza składowych głównych, analiza skupień