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ASSESSMENT OF THE POSSIBILITY OF USING WASTE AGGREGATE DUST FOR THE PRODUCTION OF VIBRO-PRESSED CONCRETE PAVING BLOCKS

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ABSTRACT: Significant amounts of rock dust with a grain size similar to cement are generated during aggregate dedusting in the production of mineral-asphalt masses. These wastes are collected in tanks or silos and must be managed in such a way as not to generate costs related to disposal. On the other hand, the use of natural resources must be reduced in the production of cement composites. The objective of this research is to investigate the possibility of utilising aggregate dedusting waste (ADW) in vibro-pressed concrete paving blocks (VPCPB). Stage one of this research includes testing the compressive strength of concrete samples where cement was partially replaced by ADW or/and fly ash (FA). Stage two discusses the effect of cement replacement by ADW or FA on the splitting tensile strength of VPCPB. Using ADW in VPCPB is a promising option. Splitting tensile strength increased after both 7 and 28 days when ADW was used.

KEYWORDS: waste management, waste aggregate dust, concrete, vibro-pressed concrete paving block, splitting tensile strength

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Introduction

The construction sector is described as one of the most carbon-intensive. Not only is it a huge energy consumer, butit is also responsible for water consumption the use of raw materials, and emits significant amounts of waste. Globally, the construction industry has the biggest environmental impact: it consumes 40% of total energy production,12-16% of water, 32% of non-renewable and renewable resources, produces 30-40% of all solid wastes, and emits 35-40% of CO_2 (Darko et al., 2017). According to UN Global Compact Network Poland (2022) in the European Union, the statistics per year for the construction industry are as follows: 1.8 billion tons of primary raw materials (25% of the total demand) and 0.8 billion tons of wastes (36% of total wastes). This indicates that the construction industry must undergo a thorough transformation. Considering this significant environmental, economic, and social impact, the sustainable management of natural resources in this sector is a necessity.

Concrete is the most popular building material around the world. Global cement production is approximately 4.1 billion tons per year (U.S. Geological Survey, 2020). According to the World Cement Association, global cement production is expected to reach 8.2 billion tons by 2030 (Tkachenko et al., 2023). The cement industry is one of the largest emitters of carbon dioxide, generating over 7% of the total global greenhouse gas budget (Tkachenko et al., 2023). Therefore, there is a strong tendency to reduce the use of natural resources in the production of building materials. It is particularly beneficial to replace materials that require the use of natural resources with recycled substitutes derived from industrial wastes.

Mineral additives have become an integral component of concrete. They partially replace Portland cement, the production of which is energy-intensive and burdensome for the environment. Natural materials, industrial waste, by-products from various industries, or other materials that consume less energy to produce than cement production are used. Materials such as fly ash, blast furnace slag and silica fume are widely used as partial cement replacements. They are called Supplementary Cementitious Materials (SCMs). However, recently, the supply of high-quality fly ash or slag has become a problem in many regions of the world (Dobiszewska et al., 2023).

It is estimated that in 2018, the cement industry in Poland used 1.5 million tons of fly ash. As a result of the decarbonisation policy in the energy sector, coal combustion is being reduced, which results in a decrease in the availability of high-quality fly ash (Kapczyńska, 2020). Therefore, cement and concrete producers try to supplement the deficiencies with other ingredients, including stone dust or recycled concrete. The limited availability of commonly used SCMs forces the search for alternative additives for use in the building materials industry. Rock dust waste is one of the potential alternative raw materials to partially replace cement.

Different types of rock powders like basalt, marble, granite, and limestone dust were studied, but they were mostly used as a partial fine sand replacement. Based on the literature review, it can be concluded that most researchers used quarry dust as a filler for the production of cement composites (Binici et al., 2007; Kabeer & Vyas, 2018; Rajput, 2018; Rodrigues et al., 2015; Topcu et al., 2009). Silva et al. (2023), based on a review of over 140 journal articles, found that the optimal range for replacing natural sand with stone dust is between 41% and 58%. Concrete mechanical properties exhibited a decreasing trend with higher stone dust contents, primarily attributed to increased voids and reduced transition zones.

The research (Vardhan et al., 2019) proved that compressive strength and splitting tensile strength of concrete mixes increased upon replacing natural river sand with waste marble powder; such composites also exhibited denser microstructure. This can be attributed to the filler effect of marble powder and the improvement in the binding ability of the mixes. Also, densification of the mix was achieved by the improvement in the binding ability due to the presence of the calcium carboaluminate phase.

The basalt powder replacement of up to 20% of sand improves the compressive and flexural strength of mortar, which is mainly attributable to the improved particle packing leading to better compaction and densification of the structure of the hydrated cement paste (Dobiszewska & Barnes, 2020).

Vijayalakshmi et al. (2013) tested the replacement of natural sand with granite powder waste and concluded that the level of replacement up to 15% is favourable for the concrete without adversely affecting the strength and durability, with a recommendation that the granite powder waste should be subjected to a chemical bleaching process to increase the sulphate resistance.

However, the use of rock dust as a partial replacement for cement often results in some decrease of the mechanical properties of cement composites at higher doses, but it is nevertheless considered to be economically and ecologically justified and in line with the principles of sustainable development (Corinaldesi et al., 2010; Dobiszewska et al., 2023). The use of marble dust up to 15% as cement replacement or as sand replacement positively affects the steel-concrete bond strength and can produce less porous concrete compared with concrete without marble dust (Aliabdo et al., 2014).

Researchers and entrepreneurs undertake work in the field of industrial waste application that will preserve or improve the performance features of modified materials while reducing the demand for natural resources and decreasing disposal costs.

Rock dust, when applied as partial cement replacement, can be considered an additive. European standard EN-206 defines additions (the English term “addition” is used in this standard, while in the literature, the synonym “additive” is commonly used) as finely divided materials used in concrete in order to improve certain properties or to achieve special properties. Two types of inorganic additions are distinguished in this standard: type I – nearly inert additions, type II – pozzolanic or latent hydraulic additions. Type I includes mineral fillers and pigments. Type II additions should have about the same fineness as cement; thanks to their physical properties, they have a beneficial effect on some properties of concrete. They are usually chemically inert, but if they have some pozzolanic or hydraulic properties or react harmlessly with the products of the reaction in the hydrated cement paste, this is an added value. The physical influence of rock dust on cement hydration is related to the filler effect and the diluting effect. The third effect is the enhancement of cement hydration by acting as nucleation sites (Neville & Brooks, 2010). At low cement replacement with inert dust, the filler effect and heterogeneous nucleation play a more dominant role than the cement dilution effect. In such cases, only a minimal reduction or even a slight increase in the compressive strength of cement composites has been observed (Dobiszewska et al., 2023).

The chemical and mineral composition of rock dust, and consequently its potential chemical activity in cement paste, depends on the type of bedrock from which it originates. Considering the oxide composition, limestone and marble dust contain mainly calcium oxide CaO. Granite or basalt dust contains mainly silicon dioxide SiO_2 and up to several percent of aluminium oxide Al_2O_3. The action of limestone dust is based on three mechanisms: dispersion of clinker grains and filling of free spaces between them, epitaxial influence on the crystallisation of the calcium silicate hydrate (CSH) phase and chemical reaction with aluminates to form hydrated carbonate aluminates (Kurdowski, 2010). Abdelaziz et al. (2014) found the pozzolanic activity of basalt dust based on thermal analysis of cement mortars after different curing times.

The subject of this study is concrete with the addition of rock dust, which is a waste generated in the production of asphalt mixture for road pavements. It is a result of the dedusting of aggregate. Such waste is also generated in aggregate production plants used in construction. A typical asphalt plant generates about 5000 tons of waste dust per year which (is approximately 5% of aggregate mass used in the production of asphalt mixtures) (Dobiszewska et al., 2023). Due to the use of aggregates from rocks with different petrographic characteristics, this waste material is also characterised by a diverse mineral composition. As a consequence, this affects the variability in its properties, which should be controlled before using this material as a by-product. Waste generated as a result of aggregate dedusting is not hazardous, and it does not undergo significant physical, chemical, or biological transformations. As it is a mineral material, it could be used in concrete production as cement pr aggregate replacement. Dust disposal is currently a problem faced by manufacturers of asphalt mixtures.

Dobiszewska (2014) studied the addition of such mineral dust as a partial aggregate substitution in concrete in the range from 2 to 10% of the total aggregate content and concluded that 6% replacement by mass increased the compressive strength of concrete by 18.6% compared to concrete without the addition of waste dust, while 10% replacement level resulted in a 35% increase in compressive strength.

In this study, the waste material from aggregate dedusting (aggregate dedusting waste ADW) was used as cement or fly ash (FA) replacement in concrete samples and as FA replacement in vibro-pressed concrete paving block (VPCPB) production. The maximum adopted substitution level was the same as in the previous study (Dobiszewska, 2014) for aggregate substitution (10%). This limit was also dictated by the desire to avoid excessive dilution effect and thus increase in the effective water-to-cement ratio.

Materials

Rock aggregates of various origins are used for the production of asphalt mixtures for road pavements. In the technological line, the aggregate must be dried and heated. It is fed to a drum dryer, where dedusting processes take place. The duration of the process and temperature of the aggregate at the exit of the dryer are adapted to the type of mixture produced. Usually, the temperature is approximately 200°C. The first stage of dedusting of aggregate takes place at the exit from the dryer. This is a very important process because dust present on the surface of the coarse aggregate grains can significantly deteriorate the affinity with the asphalt binder and, consequently, reduce the quality of the mixture. The exhaust gases leave the dryer, capturing the stone dust from the aggregate, and are extracted by the exhaust fan. The separator precipitates coarser fractions of stone dust; fine fractions are retained in a fabric filter. The latter are collected in a special tank or silo and constitute a production waste. During sorting, the remaining dust is extracted – this is the second stage of dust removal. The production of asphalt mixture uses hard mineral aggregate, which comes mainly from mines, which means that the resulting dust has properties similar to the parent rock.

For this study, ADW was collected from the asphalt mixture plant, which uses aggregate from postglacial deposits, which means the varied petrographic composition of this waste. Rock dust is irregular in shape, sharp-edged, and has a rough surface texture. The shape of the particles is very similar to cement particles (Figure 1). Density is 2.76 kg/dm^3, chloride content < 0.01%, total sulphur content 0.16%. This means that due to the chemical requirements, the analysed dust is suitable for use in concrete. Scanning electron microscope (SEM) images of ADW, cement and FA are shown in Figure 1.

Portland cement CEM I 42.5, complying with the PN-EN 196-1 requirements, was used in concrete laboratory samples and in VPCPB production. Siliceous fly ash (FA) with a density of 2.12kg/dm^3 was used as a reference additive.

Acrylate-based range-reducing admixture – superplasticizer (SP) was used to achieve the assumed slump of concrete samples prepared in the laboratory. Water reducing admixture (WRA) intended for vibro-pressed products was used to produce VPCPB.

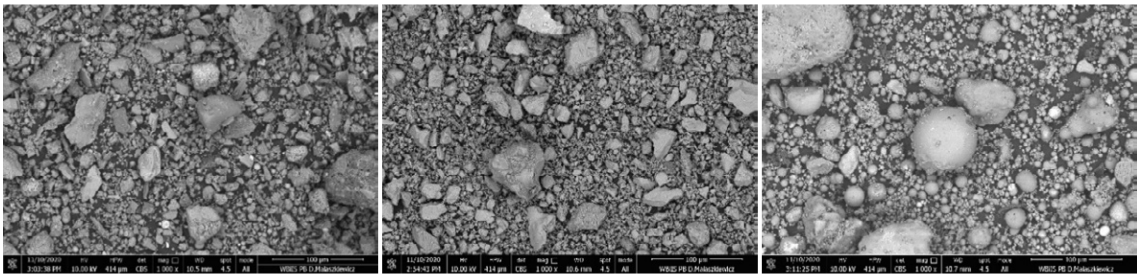
a) b) c)

Figure 1. SEM images: a) ADW, b) cement CEM I 42.5 and c) FA

Experimental program

The study was divided into two stages. Stage one included testing strength properties of concrete cubic samples compacted in a laboratory by vibration. They varied in binder proportions. First, a recipe for concrete without additives was designed, and then the mass of cement was partially replaced with 10% (by mass) FA or ADW or both additives together (FA 5% and ADW 5% by mass). Differences between cement density and densities of additives were taken into account; hence, the aggregate mass was adjusted in the modified mixtures. The composition of the individual concrete series is given in Table 1. The consistency class was assumed to be S3 (cone slump 140 to 160 mm), and the water to binder ratio was 0.53. Both FA and ADW were first mixed with cement, then aggregate was added, and all dry ingredients were mixed. Then water was added along with water superplasticiser. The scope of the research included determining the effect of the addition on the compressive strength after 2; 7; 28, and 56 days.

Table 1. Composition of concrete samples

Component	Mass per 1 m^3, kg			
	CEM100	FA10	ADW10	FA5ADW5
CEM I 42,5; kg	310	279	279	279
FA; kg	0	31	0	15,5
ADW, kg	0	0	31	15,5
Water, dm^3	164,3	164,3	164,3	164,3
Sand 0/2 mm	780	776	778	777
Gravel 2/16 mm	1170	1165	1167	1166
SP, % b.m./kg	0,8/2,48	0,8/2,48	0,8/2,48	0,8/2,48

Stage two concerns the effect of the type of additive on the splitting tensile strength of VPCPB. The composition of the binder was modified to make concrete intended for the structural layer of vibro-pressed products. In the first series, a typical composition from the production line was used, i.e. the binder was a mix of cement CEM I 42.5 (84,7% by binder mass) with the addition of FA (15.3% by binder mass). In the next two series, waste from aggregate dedusting (ADW) was also used as an additive. In the FA_AWD series, 7.65% of FA and 7.65% of ADW were used in the binder by mass. In the ADW series, FA was completely replaced by ADW, i.e. it constituted 15.3% of the binder mass. Compositions per 1 m^3 of concrete mix of individual series of VPCPB are presented in Table 2. The VPCPB were produced with nominal dimensions: height 80 mm, length 200 mm, width 100 mm.

Table 2. VPCPB composition

Composition	Mass per 1 m^3, kg		
	FA	FA_ADW	ADW
CEM I 42,5	260	260	260
FA	47	23,5	0
ADW	0	23,5	47
Sand 0/2 mm	993	993	993
Gravel 2/8 mm	960	960	960
WRA	1,87	1,87	1,87
Water	to obtain the right moisture content in the mixture		

The tensile splitting strength of VPCPB was tested after 7 and 28 days in accordance with PN-EN 1338. The strength was determined on 8 specimens for each series and calculated according to the formula:

$$T = 0.637 \cdot k \cdot \frac{P}{S}. \tag{1}$$

where:
T – strength, MPa,
S – fracture area, mm^2; S = l x t,

l – the average of two measurements of the length of the fracture, one made at the top and one at the bottom of the paving stone; mm,
t – the thickness of the paving stone in the plane of the fracture – the average of the three measurements, one in the middle and two at each end, mm,
P – breaking load, N,
k – correction factor of the thickness of paving stones.

Results and discussion

Compressive strength results of all mixes at various ages are presented in Figure 2. Replacing 10% of cement with ADW resulted in a decrease in the compressive strength of concrete samples at all test dates. However, the 5% substitution of cement did not negatively affect the compressive strength of concrete. The strength after 2, 28 and 56 days of hardening of concrete samples, where 10% of cement was replaced with FA or a mixture of FA and ADW in equal proportions, did not differ from the strength of samples with cement only.

The impact of rock dust, which generally is considered as chemically inert material, on mechanical properties of cement composites is mainly related to the filler effect due to modification of particle size distribution.

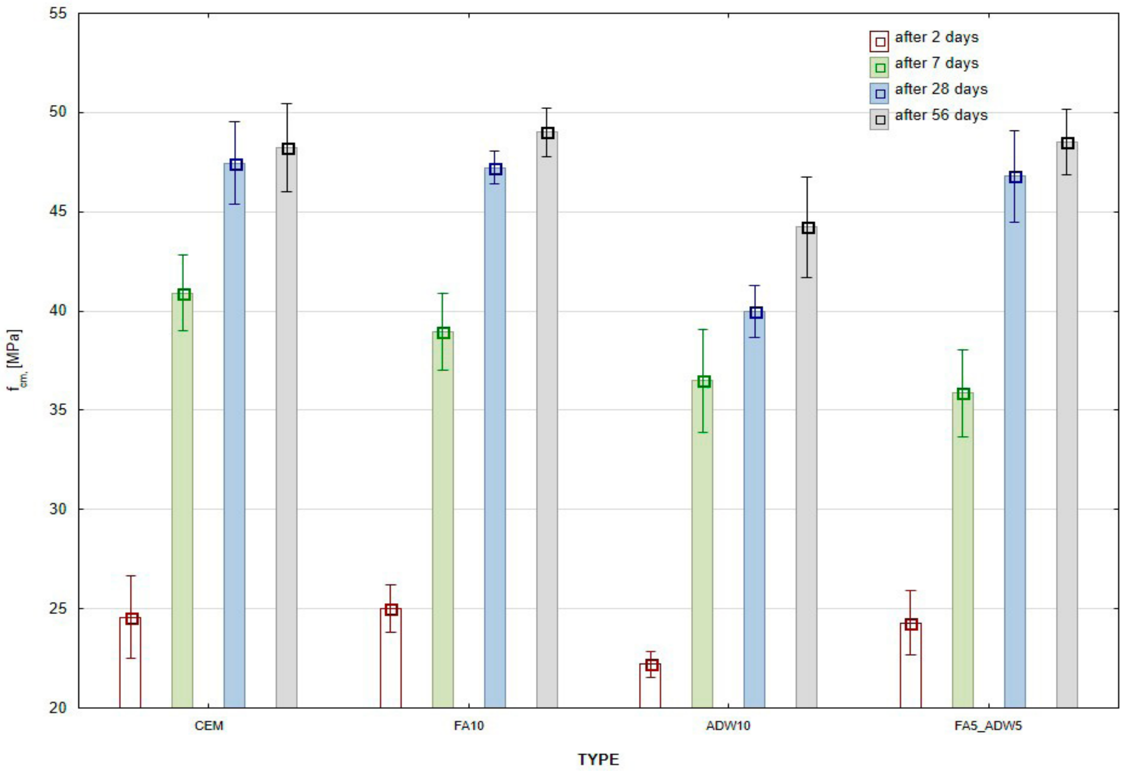

Figure 2. Compressive strength of concrete samples after 2, 7, 28 and 56 days

Using ADW as a partial cement replacement at a higher percentage reduced the compressive strength of concrete. This is caused by cement dilution and, as a result, an increase in the effective water-to-cement ratio (Dobiszewska et al., 2023). However, lower cement replacement did not negatively affect concrete strength. In this case, the filler effect and heterogeneous nucleation of cement hydrates on rock dust particles are more prominent than those of cement dilution.

Splitting tensile strength results of VPCPB tested after 7 and 28 days are given in Table 3. The original composition with FA is considered as the reference sample. The percentage difference in strength compared to the reference sample is also given in Table 3. The variability of splitting tensile strength results after 7 and 28 days are presented in Figure 3, and mean strength values with a 95% confidence interval are in Figure 4.

Table 3. Splitting tensile strength of VPCPB

	Splitting tensile strength, MPa					
	FA		FA_ADW		ADW	
	7 days	28 days	7 days	28 days	7 days	28 days
1.	3.53	3.61	3.04	3.58	3.08	3.63
2.	3.50	3.88	3.45	3,79	2.88	3.70
3.	3.33	3.47	3.54	3,94	3.69	4.10
4.	2.97	3.44	3.67	2,78	3.39	4.72
5.	3.58	3.95	3.43	3,62	3.40	3.88
6.	2.88	3.29	3.21	3,99	3.22	4.23
7.	2.66	3.53	2.95	3,97	3.25	3.75
8.	2.82	3.45	3.38	3.55	3.17	3.74
Average	3.16	3.58	3.33	3.78	3.26	3.97
Difference in strength, %	100	100	105.4	107.1	103.2	110.9

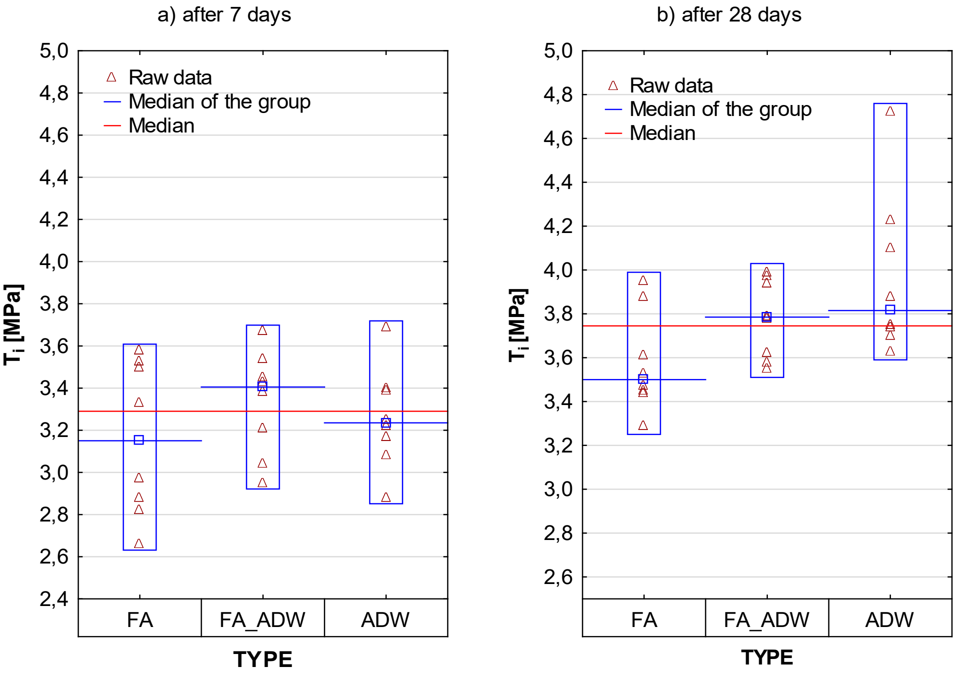

Figure 3. Variability of splitting tensile strength results after 7 and 28 days

In the case of splitting tensile strength of vibro-pressed concrete, the partial and total replacement of FA by ADW gave a positive effect. It may be attributed to the fact that the irregular, sharp-pointed particles of rock dust and cement interlock under pressurised compaction and, as a result, rock particles are more conducive to the nucleation of cement hydration products.

In order to determine the effect of the binder composition on the splitting tensile strength of VPCPB after 7 and 28 days, the univariate variance analysis test (effect A – binder type) was used. At the significance level of α=0.05, the H_0 hypothesis was verified: T_i(FA) = T_i (FA_ADW) = T_i(ADW) against the alternative hypothesis H_1: at least two mean splitting tensile strengths differ from each other after 7 and 28 days. The calculations were carried out in the STATISTICA 13.1 program. Tables 4 and 5 show the results of the variance analysis.

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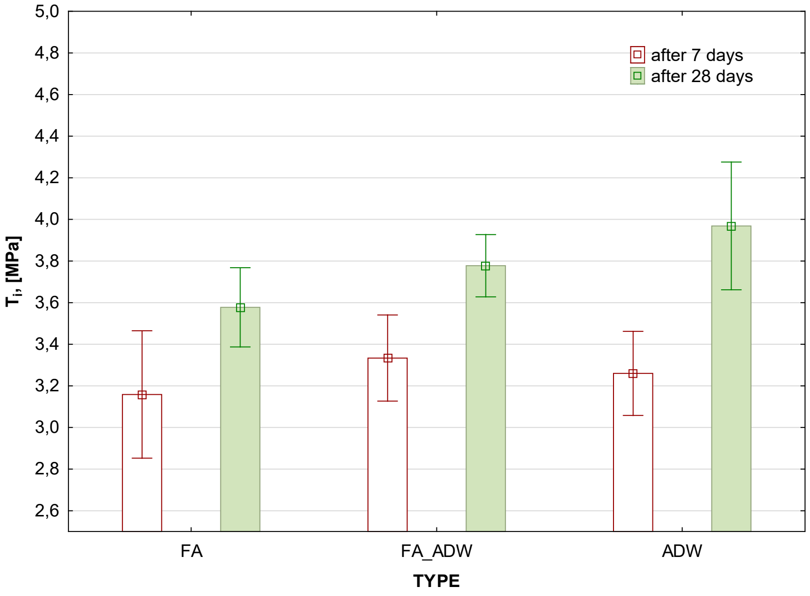

Figure 4. Mean splitting tensile strength values after 7 and 28 days with a 95% confidence interval

Table 4. Analysis of variance (*Ti* [MPa] – after 7 days)

Effect	Sum of squares *SS*	Degrees of freedom *df*	Mean sum of squares *MS*	*F*	*p-value*
A	0.123	3	0.062	0.730	0.4935
Error	1.775	21	0.0845		

Table 5. Analysis of variance (*Ti* [MPa] – after 28 days)

Effect	Sum of squares *SS*	Degrees of freedom *df*	Mean sum of squares *MS*	*F*	*p-value*
A	0.612	3	0.306	4.197	0.0292
Error	1.532	21	0.073		

It was found that at the significance level of α=0.05, there are no grounds for rejecting the H_0 hypothesis in the case of 7-day strength. This means that the test carried out on samples of a given composition did not confirm differences in the mean splitting tensile strengths T_i after 7 days. However, based on the analysis of *Ti* results obtained after 28 days, it was found that at the significance level of $\alpha = 0.05$, the H_0 hypothesis should be rejected. This means that at least between two series differing in binder composition, there are significant differences in the average splitting tensile strengths after 28 days.

In order to check which of them differ significantly, a post-hoc test was performed – Tukey's reasonable significant difference (RIR) test. It is the most recommended test for comparing pairs of averages. Based on the analysis, homogeneous groups were obtained (Table 6).

Table 6. Tukey's test results – homogeneous groups – average splitting tensile strength after 28 days *Ti* [MPa]

Homogenous groups α=0,05; error: intergroup MS = 0.0729; df = 21				
No	Type	Average *Ti* [MPa] after 28 days	1	2
1	FA	3.577	****	
2	FA_ADW	3.777	****	****
3	ADW	3.969		****

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It was found, based on the statistical analysis, that significant differences in average splitting tensile strengths were recorded between FA and ADW series after 28 days. It means that the total replacement of FA by ADW caused an increase in the VPCPB splitting tensile strength.

Conclusions

Concrete compressive strength decreased at all ages when 10% of cement was replaced by ADW, but when the replacement level was 5% the strength was not affected negatively.

A more promising option is to use ADW in the production of VPCPB. When FA was replaced by ADW, splitting tensile strength increased after both 7 and 28 days, 3.2% and 10.9%, respectively. It could be the right direction for the management of wastes generated during the production of asphalt mixtures. This approach is a step towards solving the environmental issues caused by waste generated by the construction industry. The increase in the use of alternative materials replacing Portland cement or even scarce or more expensive SCM contributes to reducing global carbon dioxide emissions and the consumption of natural resources.

Further research should include durability tests (i.e. freeze resistance) to confirm the suitability of ADW for vibro-pressed products. The physical properties of ADW, such as fineness, density, shape and texture of individual grains, as well as the chemical properties, may vary depending on the type of aggregate used in asphalt mixture production. Therefore, it is recommended to investigate the suitability of such rock waste when changing the type of aggregate in the production of the asphalt mixture or using waste from another plant.

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The contribution of the authors

Conceptualization, D.M. and B.G.K.; literature review, D.M. and M.W.; methodology, D.M.; formal analysis, D.M. and M.W.; writing, D.M. and M.W.; conclusions and discussion, D.M.

The authors have read and agreed to the published version of the manuscript.

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OCENA MOŻLIWOŚCI WYKORZYSTANIA ODPADOWEGO PYŁU Z KRUSZYW DO PRODUKCJI WIBROPRASOWANYCH BETONOWYCH KOSTEK BRUKOWYCH

STRESZCZENIE: Podczas odpylania kruszywa w procesie produkcji mas mineralno-asfaltowych powstają znaczne ilości pyłu skalnego o uziarnieniu zbliżonym do cementu. Odpady te gromadzone są w zbiornikach lub silosach i należy je zagospodarować w taki sposób, aby nie generować kosztów związanych z ich składowaniem. Z drugiej strony przy produkcji kompozytów cementowych należy ograniczać zużycie zasobów naturalnych. Celem badań jest ocena możliwości wykorzystania pyłu odpadowego z odpylania kruszywa (ADW) do produkcji wibroprasowanej betonowej kostki brukowej (VPCPB). Część pierwsza badań obejmuje porównanie wytrzymałości na ściskanie próbek betonowych, w których cement został częściowo zastąpiony ADW i/lub popiołem lotnym (FA). W części drugiej zbadano wpływ częściowego zastąpienia cementu przez ADW lub FA na wytrzymałość na rozciąganie przy rozłupywaniu wibroprasowanej kostki. Wykorzystanie pyłu odpadowego w produkcji wibroprasowanej kostki brukowej jest obiecującą opcją. Wytrzymałość na rozciąganie przy rozłupywaniu wzrosła zarówno po 7, jak i 28 dniach, gdy zastosowano ADW.

SŁOWA KLUCZOWE: gospodarka odpadami, odpadowy pył z kruszyw, beton, wibroprasowana betonowa kostka brukowa, wytrzymałość na rozciąganie przy rozłupywaniu

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