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ECOLOGICAL, TECHNICAL AND ECONOMIC ASPECTS OF USING FLINT WASTES AS AGGREGATE FOR SPECIAL CONCRETES

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ABSTRACT: This paper examines the ecological, technical, and economic aspects of using flint wastes extracted during the chalk extraction. The study presents the adverse effects of mining on the environment and draws attention to the mining waste generated. Flint wastes are proposed to be used in the crushed form as a substitute for high-quality aggregate for cement composites. Traditional concretes, which contained gravel and basalt aggregates in their volume, were used as control composites. Due to the satisfactory results of the technical tests, the described waste disposal method was also analysed in terms of possible economic benefits. Conclusions from the conducted tests proved that crushed flint waste is technically equal to high-quality special aggregates. At the same time, the costs of its acquisition and production in suitable deposition systems can be lower than the cheapest traditional gravel aggregates available on the market.

KEYWORDS: flint waste, green concrete, recycled concrete, aggressive environments, aggregate substitute

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Introduction

Regardless of the industry for which the raw materials are extracted, any mining activity involves interference with the natural environment (Uberman et al., 2014). The extraction of minerals, including those that supply organic farms, often causes irreversible changes in the landscape, alters water relations and depletes raw material resources. Even though legal regulations in the mining law are becoming stricter (Lipinski, 2021) in favour of environmental protection and force entrepreneurs to minimise the impact of extraction, processing and use of mineral resources, this activity is still not indifferent to ecosystems. Currently, the mining lobby more and more often emphasises that the reclamation of areas occupied by mining and their use for purposes such as tourism creates new values of higher utility value (Nieć et al., 2008). However, irreversible depletion of mineral resources forces rational consumption, recycling, and use of substitutes, ultimately limiting the occupation of areas to exploit new deposits and reducing the impact on the natural environment (Kudełko & Nitek, 2011).

An often overlooked fact in terms of the environmental impact of mining is the changes to the landscape caused by mining or processing waste dumps. Even though low-waste technologies are increasingly being used, the amount of waste produced is still considerable. Around 50 million tonnes of waste are generated annually in the mining industry. Waste from mining processes accounts for 20% of the total, with the remainder coming from tailings. Only about 15% of the mining waste produced is used. Most of the waste is used for engineering works consisting of filling embankments and recultivation of the resulting excavations (Kasztelewicz, 2010). Such activities often do not use the potential of the extracted waste materials, which results in irretrievable loss of energy already consumed in their extraction.

One of the mineral resources used on a large scale in agriculture, carried out using the open-pit method, is chalk deposits. Chalk is a calcareous sedimentary rock characterised by a high content of calcium carbonate and a very fine-grained structure. It is used in many branches of industry: in the rubber, paper, chemical, pharmaceutical, cosmetic, ceramic and cement industries, in the production of paints and varnishes, plastics, building materials and in agriculture as fertiliser chalk for liming soils and animal husbandry as fodder chalk. In Poland, it occurs mainly in the Lublin region in formations of the Cretaceous period and in the north-eastern part of Poland, where Cretaceous formations occur in glacial till within Quaternary formations. Its comprehensive geological resources are estimated at 206 million tonnes. Chalk extraction in 2020 in Poland totalled 0.239 million tonnes (Szuflicki et al., 2021). In the process of opencast chalk mining, the mining waste that goes to the

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dumps is flint. Flint is a sedimentary, siliceous (SiO_2), cryptocrystalline rock that occurs in several forms: tubular, spherical, lenticular or loaf-shaped concretions around non-siliceous stones such as limestone, dolomite or marl. Flints usually form biaxially with the sediments that surround them. They consist of organic silica from the dissolution of skeletons derived from invertebrates, including siliceous sponge needles. They can also be formed secondarily, around much older rocks, by silica precipitation in solutions that circulate between fractures and cracks. Due to its high technical parameters such as high hardness (5.5-7 on the Mohs scale), high density of 2.58-2.91 kg/dm^3, flint has been used for centuries to manufacture tools or weapons. These characteristics are used to produce grinding balls in mills or friction materials (Ryka & Maliszewska, 1991). The features mentioned above of this waste material allowed the author of this article to hypothesise its possible use as an aggregate for cement composites. Such an action would be in line with the environmental policy (Bukowski, 2014), which assumes the use of as many recyclates as possible in the production of new products, thinking that products are obtained that are at least no worse than those made from natural raw materials.

Literature review

To implement the above policy and reduce the adverse effects of mining activities, multi-level scientific work is being carried out. The main direction of these activities is the search for new substitutes for natural raw materials among waste substances, whose technical parameters would be at least as good as those of traditional substrates. The use of waste as a substitute for raw materials taken from the environment, on the one hand, reduces the level of mineral extraction and, on the other, results in the rational neutralisation of waste. Examples of implementing such a system of activities include mining construction aggregates and producing the so-called "green concretes". At least 30% of waste materials of different origins are used to produce them. World literature proves that such actions are possible and not only beneficial from the ecological point of view. The use of local waste to produce composites is also beneficial from an economic point of view. Producers of waste have the chance to deposit it free of charge.

On the other hand, producers of composites can obtain raw materials for their production at no cost. An example of such a circulation of materials can be found in scientific studies of sanitary ceramic waste. They prove that these materials not only can act as substitutes for traditional aggregates but they can be used in unique composites such as ultra-high-strength composites (Zegardło et al., 2016), those resistant to chemically aggressive environments

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(Ogrodnik et al., 2017) accumulating heat, resistant to high temperatures (Zegardło et al., 2018a) or fillers for resin composites (Ogrodnik & Zegardło, 2018). The construction composites industry is so wide that other waste materials such as crushed bricks (Debieb et al., 2008), clinker (Khalloo & Ali, 1994), glass from used fluorescent lamps (Zegardło et al., 2018b), glass from used windshields or concrete rubble (Hansen & Narut, 2003), demolition materials (Rao et al., 2007), etc. can also find a place in it. To reduce the energy input of composite binder production, the use of waste substances is also proposed, e.g., as a partial replacement for cement. Here, dust with binding properties such as fly ash (Atis, 2005), waste materials from stack filters, e.g., micro-silica (Shikano, 1990) or glass dust, which improve the critical processes. All the waste materials described above, playing the role of substitutes for natural minerals, cause reduction of mineral extraction, and their use is considered their rational neutralisation.

The basis for carrying out the experimental work described in this article was the pilot study of waste flint to produce cement composites initiated by the author of this article published in (Bursztyka, 2019). During the experimental work, composites were made in which the aggregate for the concretes was waste flint with grain sizes of 0-4 mm and 4-8 mm. Three series of composites were then produced in which Series I – 100% was a composite containing only waste flint as filler, Series II – 70% in which 70% flint and 30% gravel aggregate was used as filler, and Series III – 0% as a control series containing only sand and gravel aggregate. However, the concrete composition was not designed at the time. Still, it was adopted as for composites traditionally produced on concrete plants with a very low W/C ratio, i.e. as for composites with the consistency of damp earth. This fact caused that grains of flint aggregate with a very peculiar structure of flat lamellae were not arranged uniformly in the slurry. With the increase in the amount of recyclate in the composite, the number of open pores between the aggregate grains increased. The results obtained for the basic technical parameters are presented in Table 1.

Table 1. Test results of the basic technical parameters of the composites

No.	Type of composite / parameter tested	Average intended specific density of the samples [kg/dm^3]	Average measured absorbability of the samples [%]	Average measured flexural strength [MPa]	Mean measured compressive strength of specimens [MPa]
1	I – 100%	0.99	6.09	8.62	35.54
2	II – 70%	1.17	5.35	8.68	39.26
3	III – 0%	1.27	5.72	8.72	44.39

Source: Bursztyka, 2019.

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The density and absorbability tests confirmed the presence of air voids within all the composites produced, including the control ones. The tests of strength parameters, even though they showed a certain decreasing tendency with the amount of waste aggregate used, were satisfactory. Such concretes had technical parameters qualifying them as structural concretes despite their then foreseen much less restrictive use as local road foundations in chalk mines. These experiments prompted the author of this paper to repeat the research with a new objective and two assumptions based on previous experience. The first assumption was to compose a structural concrete containing only precipitated silicate aggregates, with no air voids. The experiment assumed the production of a composite with a much more liquid slurry, i.e. a lower W/C ratio. All the spaces between the aggregate grains remained filled with slurry. The second assumption was to reduce the size of the silicate grains. This was dictated by an earlier observation of 4-8 mm grains, which were flaky in shape. Grains smaller than 4 mm were more oval, which was expected to align the grains better. The starting point in the research work presented in this paper was the rock of control – basalt composites resistant to chemically aggressive environments, which was introduced in (Zegardło et al., 2018c). The economic aspects of using waste flint as an aggregate for concrete composites were analysed concerning the data in (Tokarski & Zegardło, 2020).

Materials used in the study

Aggregates

The primary material used in the experiments was flint extracted as waste from the mining of fodder chalk. It originated from a spoil heap near a chalk mine located in eastern Poland. Waste lumps of bulbous form and 10-30 cm dimensions were collected from the heap and transported to the laboratory. Using the sieve method, the waste was crushed and then separated into grain sizes of 0-2 mm and 2-4 mm. Figure 1 shows the form's debris as received from the mine and after shredding.

The comparison aggregates were a traditional sand and gravel aggregate and a high-quality basalt aggregate. Before the experimental work related to the manufacture and testing of the composites, all the aggregates were subjected to the same tests as traditional aggregates for concrete. The first test carried out for all types of aggregates was the determination of the specific density, for which the standard method was used according to PN-EN1097-7:2008. The apparent density and absorbability of aggregates were tested using the traditional way according to PN-EN 1097-6:2013-11. A microscopic

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analysis of the aggregate grains was carried out for all types of aggregates. A scanning microscope was used for this purpose. Grain shape assessment analysis was carried out, and the type of grain texture was assessed; however, thanks to the use of the microscope, the work was carried out on representative grains from the group of grain sizes 2-4 mm, which were separated by the sieve method. The length, width and thickness of the representative grains which were most abundant in a given group were measured. The shape of the grains was assessed by comparing these sizes. The texture type of aggregate grains from waste materials and traditional materials was also evaluated based on (Jamroży, 2006).

a) b)

Figure 1. Flint waste from chalk extraction: a – received from the mine, b – after grinding
Source: author's work.

Table 2. Comparison of the characteristics of the aggregate obtained from recycled flint with traditional totals, which were supplemented with values taken from the literature

Type of aggregate / Properties	Unit	Flint	Sand, gravel	Basalt
Specific density	kg/m^3	2570	2650	2600-3200
Apparent density	kg/m^3	2490	1800-2000	2500-3100
Compressive strength	MPa	200-300	22-45	250-400
Modulus of elasticity	GPa	60-105	20-40	56-99
Absorptivity	%	0.15	0.6-2.8	0.1-0.4
Degree of crushing	%	5.4	8.0-16.0	3.8
Grain shape assessment	-	scaly, flat	spherical, oval	stocky, angular
Type of grain surface texture	-	glassy, smooth	rough, granular	glassy, smooth

Source: author's work based on Góralczyk & Kukielska, 2010.

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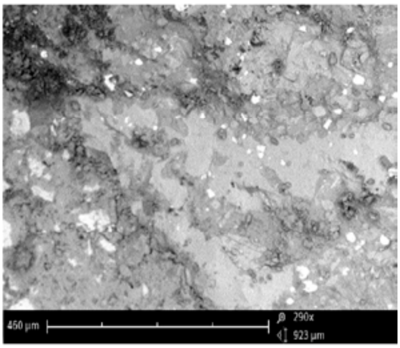
A comparison of the characteristics of the aggregate obtained from recycled flint with traditional totals, supplemented with values taken from the literature (Góralczyk & Kukielska, 2010), is presented in Table 2. Figure 2 shows representative grains of the analysed aggregates.

Figure 2.
Representative grains of analysed aggregates. From top: grains of basalt, gravel and flint

Source: author's work.

a)



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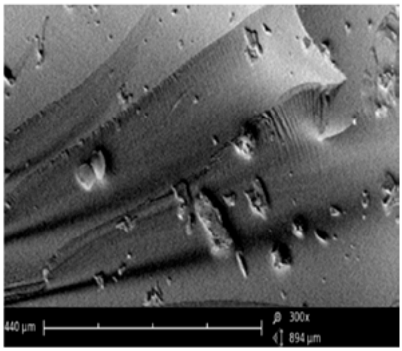

c)

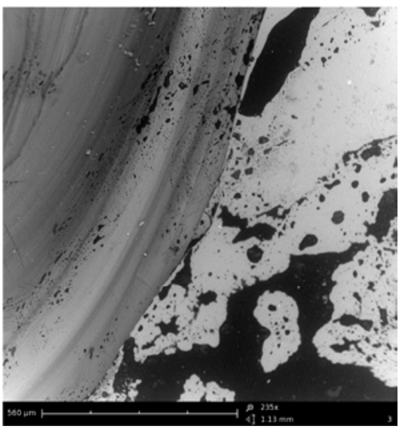

Figure 3.
SEM images: a) microscope image of a gravel grain at 450× magnification, b) basalt grain at 440× magnification, c) flint grain at 560× magnification

Source: author's work.

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A comparative analysis of the technical parameters of the aggregate made from flint waste with those recorded for traditional totals showed that they were most similar to those of high-quality basalt aggregates. The densities, water absorption and strength parameters taken from the literature were almost identical. Similarly, the surface images of the samples presented in Figure 3 were similar for both of these aggregates.

The grain surfaces of both these aggregates were smooth and vitreous in contrast to the gravel aggregates, whose surface was rough and granular. The technical parameters of the traditional sand and gravel aggregates were also significantly lower, indicating that the aggregate is more porous and less resistant than the waste aggregates. These characteristics and the proximity to basalt aggregates gave rise to the claim that aggregates obtained from waste flint could substitute for high-quality basalt aggregates.

The final test that was carried out for the aggregates was their resistance to an aggressive environment in the form of sulphuric acid. For this purpose, large aggregate grains with a size of 40-80 mm were used. Aggregate grains were weighed and immersed in an aggressive solution for 100 days. The chemical composition of the solution is presented in Table 3. The solution was gradually replenished so that the grains of aggregates remained immersed in it throughout the experiment.

Table 3. Chemical composition of the solution used to test the resistance of aggregates to aggressive environments. H_2SO_4

Solution	
Tap water	1 dm^3
Sulphuric acid H_2SO_4 (96%)	1 dm^3

Source: author's work.

The value evaluated during the test was the mass loss of grains of the tested aggregates. The test stand with selected aggregates during the experiment is presented in Figure 4.

This study proved that the flint waste aggregate has a very high resistance to the corrosive environment. The mass loss of waste aggregate grains was 3.8% and was related to the mass loss of white chalk efflorescence occurring on the waste flint. The mass loss of gravel aggregates was the greatest. The limestone grains present in the gravel were completely decomposed, and their residues in the solution formed a liquid mass. The assessed percentage mass loss here was 60.9%. The basalt aggregates were also corroded. Their outer surface was destroyed in the corrosive environment, and the assessed

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weight loss was 26.7%. The results of this study were the basis for hypothesising the potential use of the wastes mentioned above for composites resistant to chemically aggressive environments.

a) b)

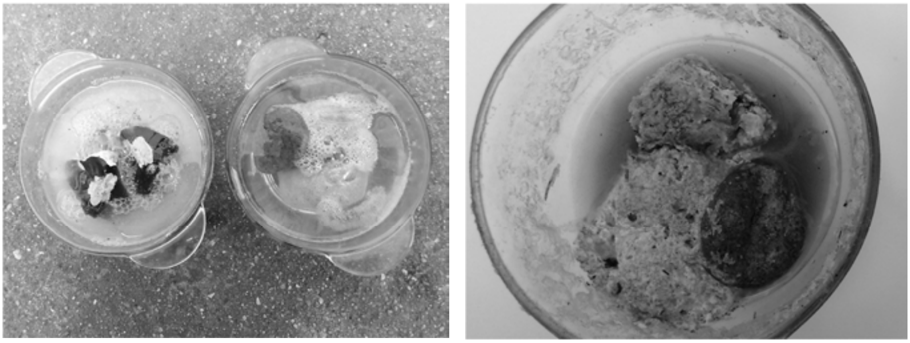

Figure 4. Test stand with selected aggregates: a) from the left: flint and gravel while testing the resistance of aggregates to chemically aggressive environment b) gravel grains which were destroyed

Source: author's work.

Further substrates used in the study were other composites components such as cement and admixtures and additives.

Cement, admixtures and additives

Portland cement CEM I 42.5N – SR 3/NA was used as cement for the composites prepared. According to the manufacturer's declaration, it has stable physicochemical parameters, adequate setting time, high early and final strength parameters, low alkali content and high resistance to aggressive chemical agents. These advantages make it popularly used in the commodity production of concrete mixes. Detailed values of the physical and chemical parameters of the cement-based on its technical sheet are summarised in Table 4.

The plasticising admixture ISOFLEX 7130 is produced with the latest hybrid polymer technology. Thanks to the knowledge of molecule synthesis, the admixture makes it possible to strongly reduce the amount of batch water, long-term maintenance of the concrete mix consistency, and homogeneity and cohesion of the concrete mix. Basic technical parameters of the admixture from its technological card are presented in Table 5.

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Table 4. Basic technical parameters of cement-based on manufacturer's technical card

Feature	Unit.	Average score	Requirements
Start of bond	min	233	> 60
End of bond	min	291	
Water efficiency	%	27.5	
Constant volume	mm	1.1	< 10
Specific surface area	cm^2/g	3688	
Compressive strengthafter 2 days	MPa	23.9	<10
Compressive strengthafter 28 days	MPa	55.9	> 42.5 < 62.5
Chemical analysis: SO_3	%	2.77	< 3.0
Chemical analysis: Cl	%	0.070	< 0.10
Chemical analysis: Na_2O eq.	%	0.53	<0.6

Source: manufacturer's technical card.

Table 5. Basic properties of the plasticising admixture based on its technical sheet

Feature	Description
Form	Homogeneous liquid
Colour	Brown
Density (20°C)	1.075 +/- 0.02 kg/dm^3
pH	5 +/- 1
Cl^- ion content	up to 0.1 %.
Alkali content calculated as Na_2O	up to 2.0 %

Source: manufacturer's technical card.

Micro-silica in the form of finely grained dust consisting mainly of spherical, vitrified grains was used as an additive in the concrete. According to the manufacturer's declaration, the micro silica used for the designed composites was obtained in gas cleaning of furnaces during the production of silicon-containing alloys. Its primary characteristics from the technical data sheet are presented in Table 6.

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Table 6. Basic properties of micro silica based on its technical sheet

Parameter	Unit	Value	Assessment method
Form	,-,	fine powder	visual
Colour	,-,	grey	visual
Fragrance	,-,	odourless	,-,
Density	g/cm^3	2.05	EN 1097-6
Bulk density	g/cm^3	1.1	EN 1097-3
Alkalinity	pH	less than 11.5	PN-EN-ISO 10523

Source: manufacturer's technical card.

Research methods

A working recipe for a concrete composite was used to produce the research composites, assuming its class to be C35/45. All the components used to create the composites were the same except for the aggregate. The quantity of the components was also the same each time and corresponded to the quantities presented in the paper. Three series of test composites were produced. The first series of CPF (Portland cement and flint) contained only aggregate from waste flint. The composition of this composite is presented in Table 7.

Table 7. Composition of the CPF master composite

Component	Unit	Amount
Cement CEM I 42.5N – SR 3/NA	kg	370
Aggregate: Flint 0/2 mm	kg	667
Aggregate: Flint 2/4 mm	kg	1296
Water	kg	139
Admixture ISOFLEX 7130	kg	5.6
Silica fume	kg	74

Source: author’s work.

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The next series CPG (Portland cement and gravel) contained only sand and gravel aggregate. The last series CPB (Portland cement and basalt) had only basalt aggregate.

The components of the composites were mixed, placed in moulds and subjected to the process of vibration. The samples prepared in this way were maintained in high humidity conditions for seven days, after which the samples were removed from the moulds. After removing the moulds, the samples were cured in the same environment for 21 days. After the care period, the composite samples were subjected to the basic tests to which structural concretes used for the erection of buildings are subjected to.

The density of the composites according to EN 12390-7:2009 was tested on rectangular samples of dimensions 40×40×160 mm. The standard guidelines conducted the test, and the density was calculated as the ratio of the specimen mass to its volume.

The next test was a scalability test. It was tested on samples with dimensions of 40×40×160 mm in accordance with PN-EN 1097-6:2013. The samples were immersed in water and remained there until their weight was established. Wettability was calculated as the ratio of the amount of water the composite was able to absorb to the weight of the dry composite, expressed as a percentage.

The next test was the strength test. The three-point bending strength was tested according to the guidelines in PN-EN 12390-5:2009. Samples of the same dimensions of 40×40×160 mm were prepared for the test. After this test, the beam halves were used for the next test – the compressive strength test. The compression strength of the samples was performed according to PN-EN 12390-3:2011.

By the primary assumption of the experimental work, the composite containing waste flint was also evaluated in chemically aggressive environments. The industrial application of this waste was to be the use of flint as a substitute for high-quality aggregates, which industrial concrete batching plants use to produce concrete elements of sewerage networks. The operating environment of inspection wells, pumping stations, treatment plant tanks or sewage pipes is unfriendly to concrete composites. The destructive influences here are chemical, biological, thermal and mechanical influences. Exposure to harmful agents occurs both on the inner side, where the source of aggression is the sewage environment, and on the outer side, where there is contact with the ground and groundwater. The chemical composition of aggressive agents depends on their origin. Among the wastewater transported in concrete pipes, one can distinguish municipal wastewater, agricultural wastewater from farms, rainwater contaminated with salt and products of vehicle traffic and industrial wastewater of different compositions and origins. The experimental work presented in this paper focuses on the operation of con-

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crete elements in contact with wastewater transported through general sewage systems. In accordance with the literature (Gruner, 1983), aggressive hydronium ions H_3O^+ ions (pH), sulphate ions SO_4^{2-}, ammonium ions NH_4^+ and magnesium ions Mg^{2+}.

The corrosion mechanisms planned to be induced depending on the type of aggressive agents. The intended adverse effect of acid corrosion affected all concrete components, including aggregate (Czarnecki et al., 1995). It is caused by both strong mineral acids (e.g., H_2SO_4, HCl, HNO_3), weak acids (e.g., H_2S) and organic acids (e.g., acetic acid, lactic acid and humic acid). Degradation here involves the formation of readily soluble salts by reactions (1-3):

$$Ca(OH)_2 + 2H^+ \rightarrow Ca^{2+} + 2H_2O, \quad (1)$$

$$3CaO \cdot Al_2O_3 + 12H^+ \rightarrow 3Ca^{2+} + 2Al^{3+} + 6H_2O, \quad (2)$$

$$3CaO_2 \cdot SiO_2 + 6H^+ \rightarrow 3Ca^{2+} + H_2SiO_3 + 6H_2O. \quad (3)$$

Acid corrosion leads to an increase in the porosity of concrete and a decrease in its strength. To detect it, strength tests were planned for all composites after exposing the samples to an aggressive environment.

The mechanism of another possible type of corrosion, sulphate corrosion, is based on the reaction of sulphate ions with components of the hardened cement slurry. The corrosion products are insoluble compounds, which join water in crystallisation, causing a significant increase in volume. Initially, calcium hydroxide reacts, changing to hydrated calcium sulphate in reactions (4) and (5):

$$Ca(OH)_2 + SO_4^{2-} \rightarrow CaSO_4 + 2OH^-, \quad (4)$$

$$CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O. \quad (5)$$

In the next phase, monosulphated aluminate is formed in the form of platelets:

$$3CaO \cdot Al_2O_3 + CaSO_4 \cdot 2H_2O + 10H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O, \quad (6)$$

or tricalcium sulphate alumina (*etryngite, Candlot salt)* in the form of clustered elongated needles in reaction (7):

$$3CaO \cdot Al_2O_3 + 3(CaSO_4 \cdot 2H_2O) + 26H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O. \quad (7)$$

In the initial phase, sulphate corrosion has a beneficial effect on the concrete structure, as the reaction products fill the pores and capillaries, sealing

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and consequently increasing the strength parameters (Czarnecki et al., 2007). Further growth of the crystals induces high internal stresses, leading to cracks and fractures and eventually the material's destruction.

During magnesium corrosion by reaction with calcium hydroxide, magnesium ions replace calcium ions. The product of the response is poorly soluble magnesium hydroxide, which has no binding properties, and the concrete structure is weakened according to reaction (8):

$$Ca(OH)_2 + MgCl_2 \rightarrow CaCl_2 + Mg(OH)_2. \quad (8)$$

Analogous to magnesium corrosion, calcium ions are exchanged for ammonium cations. The product is volatile ammonia and easily soluble salts, which increases the porosity of the concrete formed in the reaction (9):

$$Ca(OH)_2 + 2NH_4Cl_2 \rightarrow CaCl_2 + 2NH_4OH. \quad (9)$$

To represent the chemically aggressive operating environment of concrete sewage network elements, concrete samples were placed in water solutions of corrosive substances. Because corrosion processes are very long-lasting processes, to accelerate the effects of the aggressive environment on the composites, the answers were prepared in concentrations much higher than those occurring in the natural environment. Apart from water, sulphuric acid was added to create the solution, and ammonium and magnesium ions were introduced in the form of ammonium sulphate and magnesium sulphate. The composition of the solution is shown in Table 8.

Table 8. Composition of the solution imitating the working environment of concrete composites in sewer elements

Solution	
Tap water	7 dm^3
Sulphuric acid H_2SO_4 (96%)	7 ml
Magnesium sulphate heptahydrate $MgSO_4 \cdot 7 H_2O$	219.6 g
Ammonium sulphate $(NH_4)^2SO_4$	64.2 g

Source: author's work.

The test specimens were placed in plastic containers containing the solution. The samples are placed so that their upper surface is covered throughout the test cycle with a min layer 2 cm of solution. The samples were kept in solution for 40 days. The comparative composite samples were kept in tap water during the same period. After this period, the samples were subjected to compressive strength testing.

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The final stage of the research work carried out was an economic analysis of using waste flint by local concrete batching plants. This was done using the cost-benefit analysis method. Data were obtained from surveys conducted by producers and related to the values presented in the literature (Tokarski & Zegardło, 2020). Cost-benefit analysis is a comprehensive method of assessing the effectiveness of investments and projects, taking into account all expected benefits and costs, including qualitative and quantitative elements, and determining the degree of effectiveness of a given investment in the environment (Becla et al., 2012). In addition to the economic aspects of a project, the cost-benefit analysis also considers social, cultural and environmental areas, which are included in external costs (Boardman et al., 2006). Cost-benefit analysis is instrumental in evaluating many stakeholders projects and where profit maximisation is not the primary selection criterion. The theoretical basis for the above analysis is welfare economics (Szot-Gabryś, 2013). This paper estimates the costs and potential economic benefits of disposing of flint waste by using it to produce aggregates for speciality concrete. The proposed disposal system made them available free of charge by mining companies to local entrepreneurs producing concrete composites. It was assumed that concrete companies equipped with crushers would crush the waste and use it in concrete to replace traditional aggregates.

Results of the research

The composites' specific density and water absorption results are presented in Table 9.

Table 9. Results of testing the specific density and absorbability of the composites

Inclusion	CPT	CPG	CPB
Specific gravity [kg/dm^3]	2.552	2.382	2.546
Absorbability [%]	5.69	5.58	5.74

Source: author's work.

The tested specific density of the composite containing CPF flint waste was almost identical to that of the composite containing CPB basalt and was 2.552 kg/dm^3. The recorded difference in the density values of these two composites was less than 1%. The density value tested for the composite containing CPG gravel was slightly lower. However, this value was about 6% lower than the recorded highest value for basalt. This characteristic was likely influenced by the density of the aggregates themselves used in the study. There are grains of varied origin and structure among the gravel aggre-

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gate grains. There are grains with an open and porous structure, which affects the overall lower density of the aggregates themselves. Basalt grains and flint grains have a similar closed system, reflected in a similar tested density of both composites made of them.

The absorbability test showed a similar trend. The absorbability of the composite containing CPF flint waste was almost identical to that of the composite containing CPB basalt and was 5.69%. The recorded difference in the absorbency value of these two composites, similarly to the density, was less than 1%. The absorbency value tested for the composite containing CPG gravel was slightly lower. However, this value was about 2.8% lower than the highest recorded value for basalt. Here, as in the case of density, this characteristic was probably influenced by the composition of the aggregates themselves. The composition of the cement stone was the same in all cases, so it must have absorbed water with the same intensity. The gravel aggregate with the higher absorbability absorbed water with greater intensity than the basalt or flint. The results of this study again confirmed the similarity of the waste aggregate to basalt.

The results of the flexural strength test are presented in Figure 5.

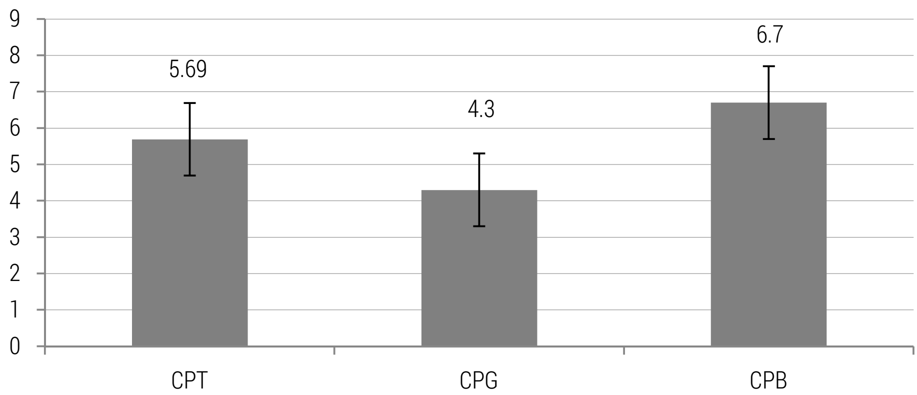

Figure 5. Test results for flexural strength of composites [MPa]

Source: author's work.

The flexural strength test results proved that the most favourable value of this parameter was recorded for the composite containing CPB basalt and was 6.7 MPa. The value tested for the other composites was lower. For the composite containing silicon CPF and gravel aggregate CPG, they were 5.69 MPa and 4.3 MPa, respectively. Therefore, the highest value recorded for the basalt was 15% higher than for the recycled concrete and 55% higher than for the gravel composite. Flexural strength is a property that is strongly influ-

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enced by the aggregate itself, while the adhesion of the total to the slurry is a factor that largely determines this parameter.

When bending, tensile stresses occur both in the aggregate itself, the cement stone and in the contact zone between the aggregate and the grout. Basalt aggregate is a high-quality aggregate with a glassy grain surface to which the cement slurry adheres compactly, forming a continuous, tight contact zone. The pores in the gravel grains mean that the zone does not adhere tightly, and contact is limited. The structure of grains of flint observed under the microscope was almost identical to grains of basalt aggregate. Therefore, it was predictable that the strength parameters were similar for both CPF and CPB composites. The slightly lower value recorded for the recycled aggregate may have been due to the presence of chalky inclusions in the flint grains. These were not clearly visible after grinding, but it is likely that the small grains contained fragments of these inclusions and therefore weakened the contact zone. However, the value observed for the recycled concrete was closer to the basalt composite.

The results of the compressive strength test are presented in Figure 6.

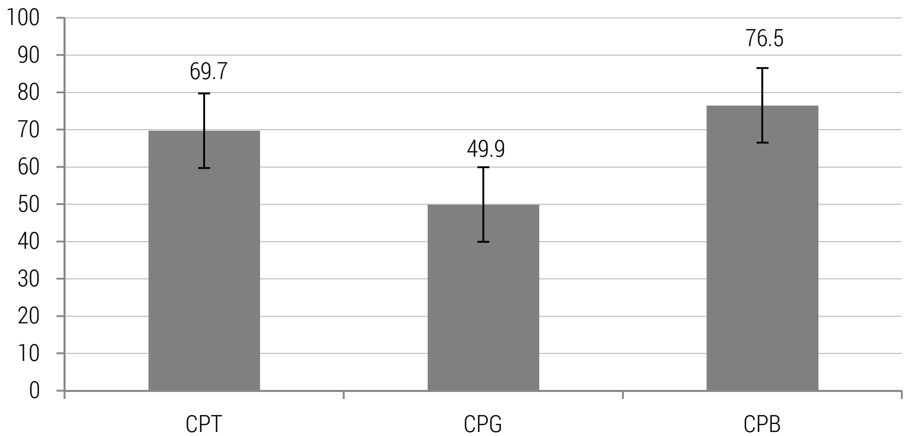

Figure 6. Compressive strength test results for composites [MPa]
Source: author's work.

The results of the composite compressive strength test again proved that the composite containing CPB basalt had the highest values. A value only 8.8% lower was recorded for the recycled aggregate containing flint and was 69.7 MPa. The value that was tested for the gravel aggregate was the lowest. It was 34% lower than the value recorded for the basalt aggregate and was 49.9 MPa. This study again confirmed the assumption that the waste aggregate was similar to the basalt aggregate. The slightly lower strength parameters observed for the recycled composite were again attributed to chalky inclusions present in the flint grains. Observation of the breakthrough of the samples after testing proved that the reduction of the composite grains and the increase in the liquidity of the mixture had a positive effect on the recycled composite. No air voids were observed in the volume of the samples and the contact zone between the flint grains and the cement was compact. The breakthrough of the recycled composite sample after compressive strength testing is presented in Figure 7.

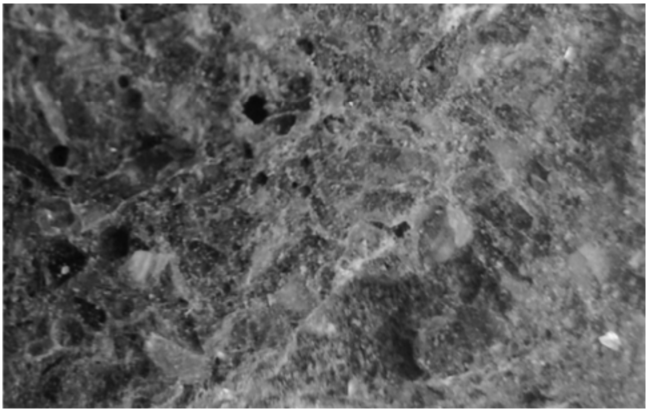

Figure 7. Breakthrough of a composite sample containing flint after compressive strength testing

Source: author's work.

The results of compressive strength testing of the composites after their exposure to a chemically aggressive environment are presented against the background of the tested strengths of the composites staying in tap water at the same time (Figure 8).

The results of testing the resistance of the composites to chemically aggressive environments showed a renewed similarity of the waste aggregates to basalt. The observed compressive strengths of recycled CPF and basalt CPB composites were very close and were 54.7 and 56.7 MPa, respectively. The difference between them was only 3.7%. The value tested for CPG gravel aggregates was 67% lower and amounted to only 18.7%. The relationship of these values to comparative values tested for composites in tap water also varied. Further decreases in compressive strength recorded for successive test series were: CPF – 26%, CPG – 63%, CPB – 27%. These values were, therefore, similarly similar for recycled and basalt composites. This study reflected the results of the resistance to aggressive environments of the aggregates themselves. The bold solution penetrated the composite structure and affected the total. Grains of gravel-carbonate aggregates underwent partial destruction in the aggressive environment. This process was the

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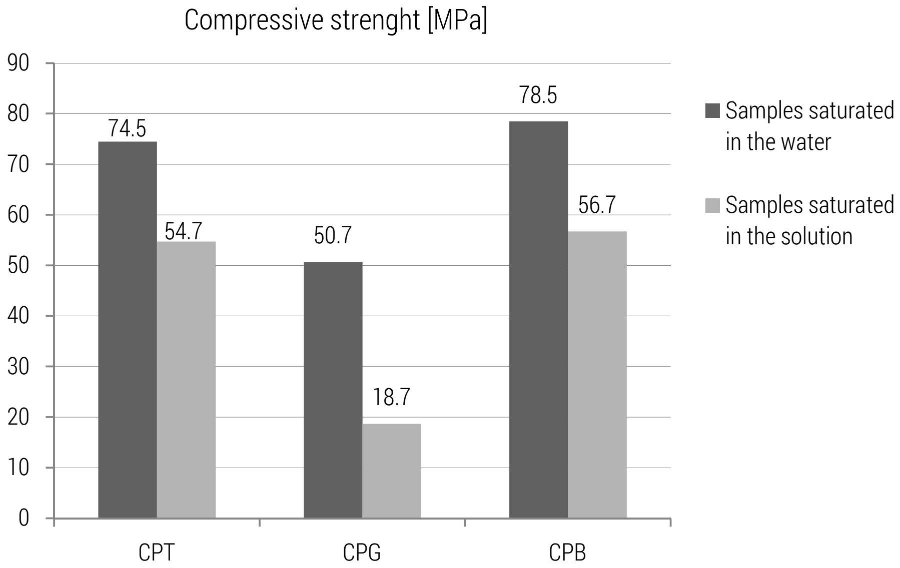

Figure 8. Results of testing the strength of composites after their exposure to a chemically aggressive environment against the tested strengths of composites residing in water [MPa]

Source: author's work.

result of the observed strength decrease. Basalt and recycled composites were characterised by a reduction of strength, which was probably influenced only by destructive processes occurring in the cement stone itself. A close-up of the breakthrough of the CPF recycled composite sample after compressive strength testing after removal from the aggressive solution is presented in Figure 9. The photograph shows that the aggressive environment penetrated the sample to a limited extent.

The depth of penetration was approximately 0.5 mm and resulted in exposure and contact with the aggressive environment of the aggregate itself. This fact confirmed the results of the strength tests and the described relationship of these results with the results of the chemical resistance tests of the aggregates themselves.

This experiment proved that both types of aggregates, flint and basalt, can fulfil the role of suitable aggregates for the composition of concretes resistant to aggressive environments.

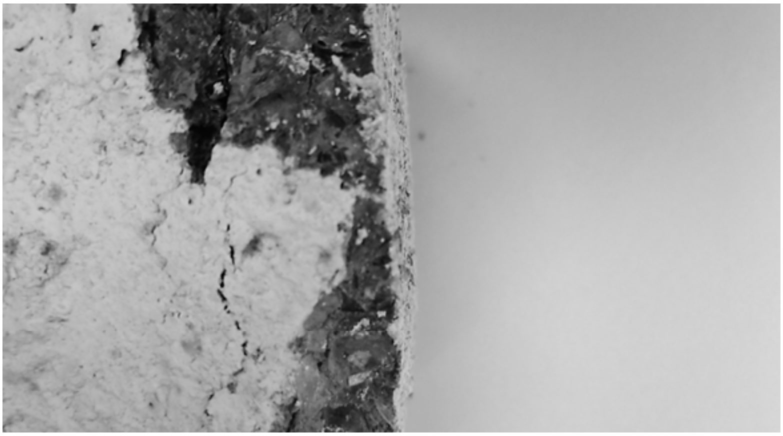

Figure 9. Close-up on the breakthrough of the CPF recycled composite sample after compressive strength testing after removal from the aggressive solution

Source: author's work.

The economic analyses were presented against the background of literature values for other traditional and recycled aggregates used in concrete batching plants (Tokarski & Zegardło, 2020). Table 10 shows the costs of transport, aggregate crushing, standardisation and other additional expenses that would have to be borne by entrepreneurs producing concrete based on the mentioned aggregates.

Analysing the data included in the table, it should be noted that the most economically justified is the use of aggregates produced based on flint. Even though this waste requires an adaptation process such as crushing, it can be a cheaper aggregate than the cheapest gravel aggregates available on the market when used in local concrete batching plants. They can be sourced as waste material at no cost, and their local use reduces transport and associated costs. As a non-absorbable aggregate, flint aggregate also does not require extraordinary expenditures for increasing the amount of cement, as is the case with concrete rubble. It is also worth noting the significant difference in the price levels of flint and basalt aggregates. Technical studies of the characteristics of these two aggregates have proved their considerable proximity. The price of an aggregate made of flint constitutes only 32% of the value of basalt aggregate price. However, according to the presented research results, both types of aggregates can be used for special purposes, such as producing composites with high resistance to chemically aggressive environments.

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Table 10. Economic analyses of the use of waste flint to produce concrete composites

Type of aggregate / Feature	Unit.	Traditional aggregate: sand, gravel	Concrete rubble of low-grade concretes	Destructive concrete for high performance concretes	Basalt grit	Waste of flint
Form in deposit	–	aggregate directly for use	large–scale elements	large–scale elements	manufactured aggregate directly for use	medium–sized elements
Deposit price (gross at retailer's)	PLN/tonne	36.9	18.45	30.75	61	0
Estimated transport distance from the deposit to the concrete producer	km	50	50	80	300	25
Transport price	PLN/tonne	12	12	19.2	72	6
Need to adapt to commodity production	yes/no	no	yes	yes	no	yes
Type of adjustment	–	–	cleaning and crushing	crushing	–	crushing
Estimated cost of compliance	PLN/tonne	–	21.07	14.76	–	37.15
Total cost in the concrete mixing plant	PLN/tonne	48.9	51.52	64.71	133	43.15
Special requirements in the production of concrete mixes	kind of	–	increasing the amount of cement	increasing the amount of cement	–	–
Input cost per 1t of aggregate	PLN/tonne	–	12.3	12.3	–	–
Total cost including additional expenditure	PLN/tonne	48.9	63.82	77.01	133	43.15

Source: author's work based on Tokarski & Zegardło, 2020.

Conclusions

Based on the conducted analyses, it may be stated that aggregate for concrete may be produced from waste flint, which is obtained as waste during chalk mining. The aggregate produced from the waste has a density, absorbability, surface structure and resistance to aggressive environments similar to those observed for high-quality basalt aggregates. These technical parameters are significantly better than those recorded for sand and gravel aggregates.

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Composites in which highly fragmented flint waste is used as the only aggregate have density, absorption, bending and compression strengths close to those of concrete composites containing basalt aggregate produced in industrial concrete plants. The high strength of waste composites classifies them as high-strength concretes and allows them to be used in structural elements. In addition, the composites produced in this way have a high resistance to chemically aggressive factors which occur in concrete elements of sewage systems. Aggressive hydronium ions H_3O^+ (pH reaction), sulphate ions SO_4^{2-}, ammonium ions NH_4^+ and magnesium ions Mg^{2+} with which the composite samples were in contact caused only a 26% decrease in the compression strength of the composite, while this parameter was almost the same as that of the comparative basalt composites.

Based on the analyses carried out, it may be stated that aggregates produced from waste flint may be a substitute for high-quality basalt aggregates with a particular recommendation for use in areas with increased chemical aggressiveness corresponding to the work of concrete elements in sewage systems.

Economic analyses show that a suitable system for the use of flint waste by local concrete batching plants producing concrete composites can be very beneficial. The costs of obtaining, transporting and crushing the waste can, in some cases, be less than the costs of obtaining traditional gravel aggregates.

According to the research results presented, the proposed system for the use of mining waste can be recommended for implementation in industrial operations. Chalk mining waste used in the above mentioned way can be a substitute for separate special aggregates. The described activities may have several levels of positive impact on the environment. The rational use of mining waste may contribute to a reduction in the extraction of natural basalt aggregates as well as the appropriate use of energy previously consumed in the extraction of the waste itself. Such activities may also have positive economic effects. Concrete batching plants operating locally next to chalk mines may have a chance to obtain a cost-free substitute for expensive special aggregates often transported from long distances.

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