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Use of Sustainable Fine-Grain Aggregates in Cement Composites

Teresa Rucińska[1]

[1] Department of Building Physics and Building Materials, Faculty of Civil Engineering and Architecture, West Pomeranian University of Technology, Szczecin, al. Piastów 50, 70-310 Szczecin, Poland
e-mail: Teresa.Rucinska@zut.edu.pl

ABSTRACT

The previous research and the analyses from various research centers indicate the usefulness of the aggregates obtained from waste in the construction materials technology, although their technical parameters are not always comparable to the properties of traditional materials manufactured on the basis of primary raw materials. However, with a very large variety of expected technical features, these slightly lower parameters may be sufficient for use in engineering facilities. Mortars and concretes are the most popular group of materials, where aggregates obtained from waste can be used without any problems. The presented characteristics of the properties of fine aggregates, which were produced by grinding concrete and ceramic debris, as well as the fragmentation of municipal sewage sludge, in connection with the properties of cement mortars, is a clear example of this. The study showed that the cement mortars, in which natural aggregate was replaced by waste glass with the same granulation, confirmed their usefulness as mortar for building masonry, or underlays for floors. However, the fact that carrying out the process of fragmentation of waste to adequately fine granulation on an industrial scale is highly inconvenient, cannot be omitted. There are no difficulties in obtaining the aggregates with larger grains, which are used in hardening unpaved roads or as a concrete component. Obtaining finer grains of recycled aggregate becomes more challenging. Overcoming this obstacle will make the fine-grained aggregates obtained through the recycling of waste materials a viable alternative to the natural aggregates. This will contribute to the reduction of the extraction of natural sands, and thus to the protection of the natural environment.

Keywords: cement mortar, mortar sustainable, recycling of aggregates, waste aggregate

INTRODUCTION

The dynamic economic growth in the recent years is one of the major reasons for high environmental pollution. An increased demand for natural resources causes shortages or even depletion of metallic ores [Brożyna and Kozioł, 2014]. Continuously increasing volume of produced waste, including construction waste, cullet or municipal waste requires immediate action. The On-going trend for using recycled materials and vast number of ongoing studies on the recycling of waste, proves the importance of this issue [Kurpińska and Ferenc, 2017, Kuśnierz, 2010, Skoczylas and Rucińska, 2018]. Actions focus on reusing the ceramic [Jura et al., 2015] and concrete waste [Bołtryk et al., 2017], fly ashes [Gołek and Kapeluszna, 2013], cullet [Sikora et. al., 2015] or municipal waste [Głowacka et al., 2017].

The aggregates acquired in the process of recycling of construction materials are frequently reused for production of concrete. [Goncalves and de Brito, 2010] studied the usage of such aggregates regarding different standards and existing laws in various countries. The scholars drew a conclusion that an effort must be made to limit the usage of resources, as recycling alone is not sufficient. Such approach allows for an effective reuse of construction waste. The technology is not only available, but it can also bring significant financial benefits.

The majority of the studies proved that the use of recycled aggregates as a partial replacement of natural aggregates, leads to significant changes in the concrete properties. The quality and type of the recycled aggregate is a key reason behind this phenomenon. As a result, the use of those concretes for engineering purposes is limited. The shape and size of the aggregate grains, original material, water absorption, varying density and granulation, all negatively influence the compressive strength, mechanical properties and durability of produced concretes [Brito, 2005, Brito et al., 2005, Limbachiya et al., 2000]. Several studies [Aly et al., 2012, Batayneh et al., 2007, Du and Tan, 2014, Evangelista and Brito, 2007] determined that the use of 25-30% of coarse recycled aggregate as an replacement showed no significant negative effects.

The study aims at determining the applicability of fine grade recycled aggregates, including cullet, concrete and ceramic construction waste and incinerated sewage sludge for the production of cement mortars. The results of laboratory tests proved that fine graded recycled waste aggregate can be used for the production of composite materials, even if they deteriorate the final product parameters. Similarly to concrete, mortars can be exposed to different conditions and used for different purposes. Therefore, the applicability of the recycled waste in mortars is limited, but still possible.

NATURAL AND RECYCLED AGGREGATES

The majority of studies on recycled aggregates focus on coarse particles [Etxeberria et al., 2007, Fonseca et al., 2011, Zhou and Chen, 2017]. However, fine milled aggregates can be used in various products, including cement mortars.

Fine natural aggregate (i.e. sand) is typically used for production of cement mortars and concretes. Other industrially used aggregates, such as lightweight aggregate include perlite, sintered PFA, or polystyrene granulate. Some studies are conducted to test the possibilities of using aerogel particles [Strzałkowski and Garbalińska, 2016]. Increasingly extended environmental protection directs us towards the use of alternative aggregates. The aggregates obtained from the recycling of waste are already considered in existing standards.

The conducted research aimed at determining if the fine graded aggregates, produced from ceramic and concrete waste, glass cullet and incinerated sewage sludge (slag) can successfully be used to replace natural sand. The composition and grading curve was presented in Table 1 and Figure 1.

Table 1. Density of natural aggregate and waste aggregates [Rucińska, 2018]]

Fine-grained aggregate	Density [g/cm^3]
Natural sand	2,65
Obtained from waste concrete	2,59
Obtained from waste ceramic	2,68
Obtained from waste glass	2,53
Incinerated sewage sludge	2,86

The first stage of recycling included milling the waste into smaller fractions and determining the grading curve. The first observation was that the shape of most milled aggregate is irregular and its surface is rough – Figure 2a, 2b, 2c, 2e). Only the cullet particles had sharp edges and smooth surface (Figure 2d).

Due to the nature of the initial material, waste aggregates, except for cullet, have high grain porosity. In the case of concrete and ceramic waste, and incinerated sewage sludge, the porosity of final product depends on the initial properties of waste. Additionally, the recycled aggregate acquired from concrete rubble is inhomogeneous. The aggregates are partially created from cement matrix and partially from the natural aggregates in the initial waste. Considering that the composition of ordinary concrete is 70% aggregate and 30% of cement matrix, it is possible to assume a similar composition for recycled aggregate. However, some parts of initial natural aggregate will be covered in cement matrix. As the cement matrix typically has porosity of around 40%, some grains of recycled concrete aggregate will have increased porosity as well. Ceramic waste aggregate and incinerated sewage sludge have a similar porosity in all grains, with ceramic being the most homogenous.

Determination of the actual porosity of waste aggregates can be difficult. The structure of initial waste differs greatly. Therefore, proper determination of mixing water volume to produce required consistency is problematic. The initial amount of water can be determined from the standard water/cement ratio. In turn, the additional amount of water must be added empirically, as waste aggregate grains absorb water to a different extent. In the case of limited or non-existing reactivity of the aggregate, the additional water will eventually evaporate. The occurrence of additional water influences the internal curing processes during the hardening and maturing of concrete, especially near the cement-aggregate contact

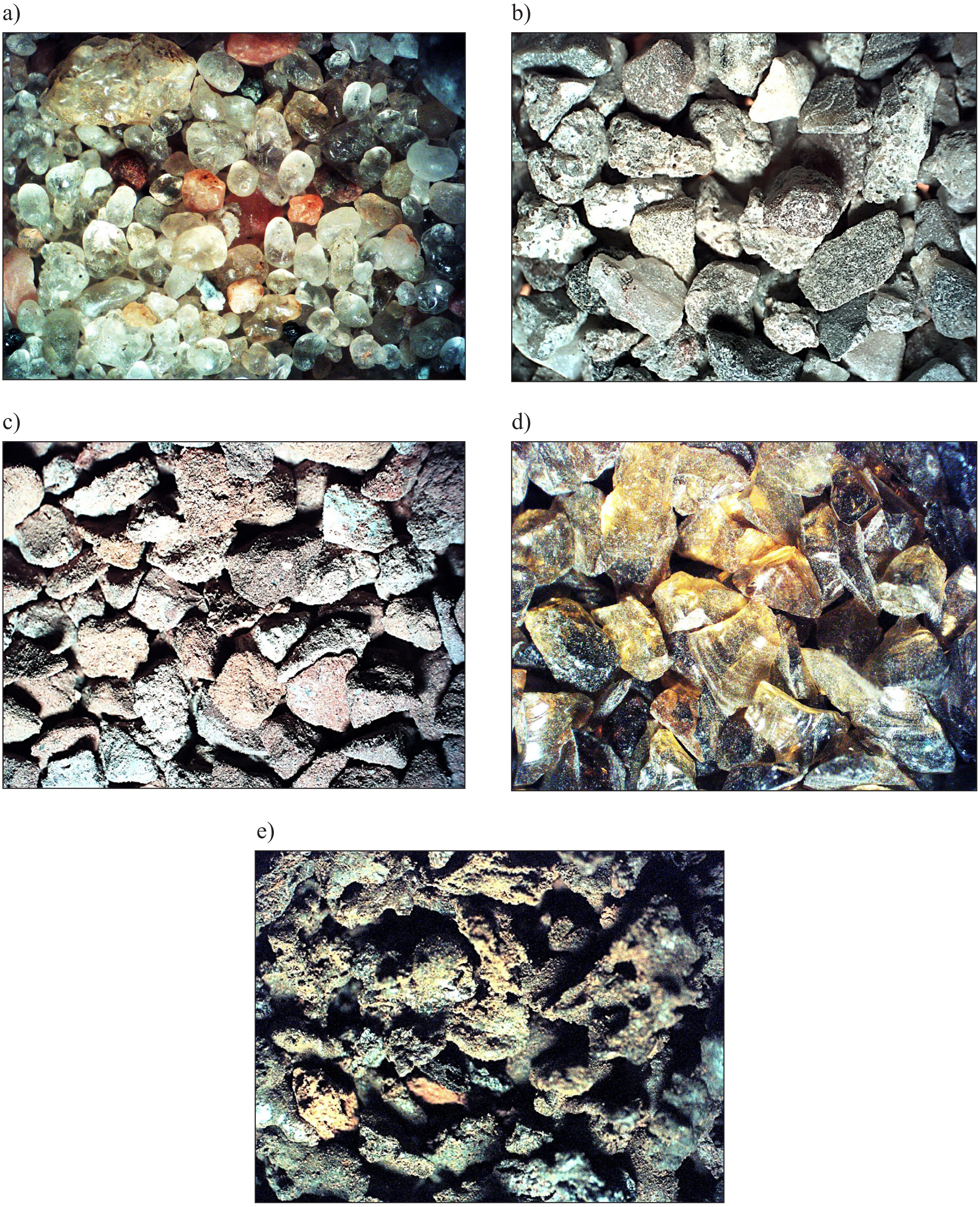


Figure 1. a) Grains of natural sand, b) Grains of ground waste concrete, c) Grains of ground waste ceramic, d) Grains of waste glass, e) Grains of incinerated sewage sludge

zone. However, the evaporating water leaves additional micropores, decreasing the durability and strength of the material. Even if the waste aggregate grains exhibit changing properties which can affect the final properties of mortars, multiple quality control tests allow determining the range for which the changes are acceptable.

The use of waste materials always has to come with proper safety measures and control to prevent the harmful effect on the human health. Figure 2 presents the EDS analysis of the compound composition of studied waste aggregate. The analysis of the composition of the natural aggregate was typical for quartz sand. The

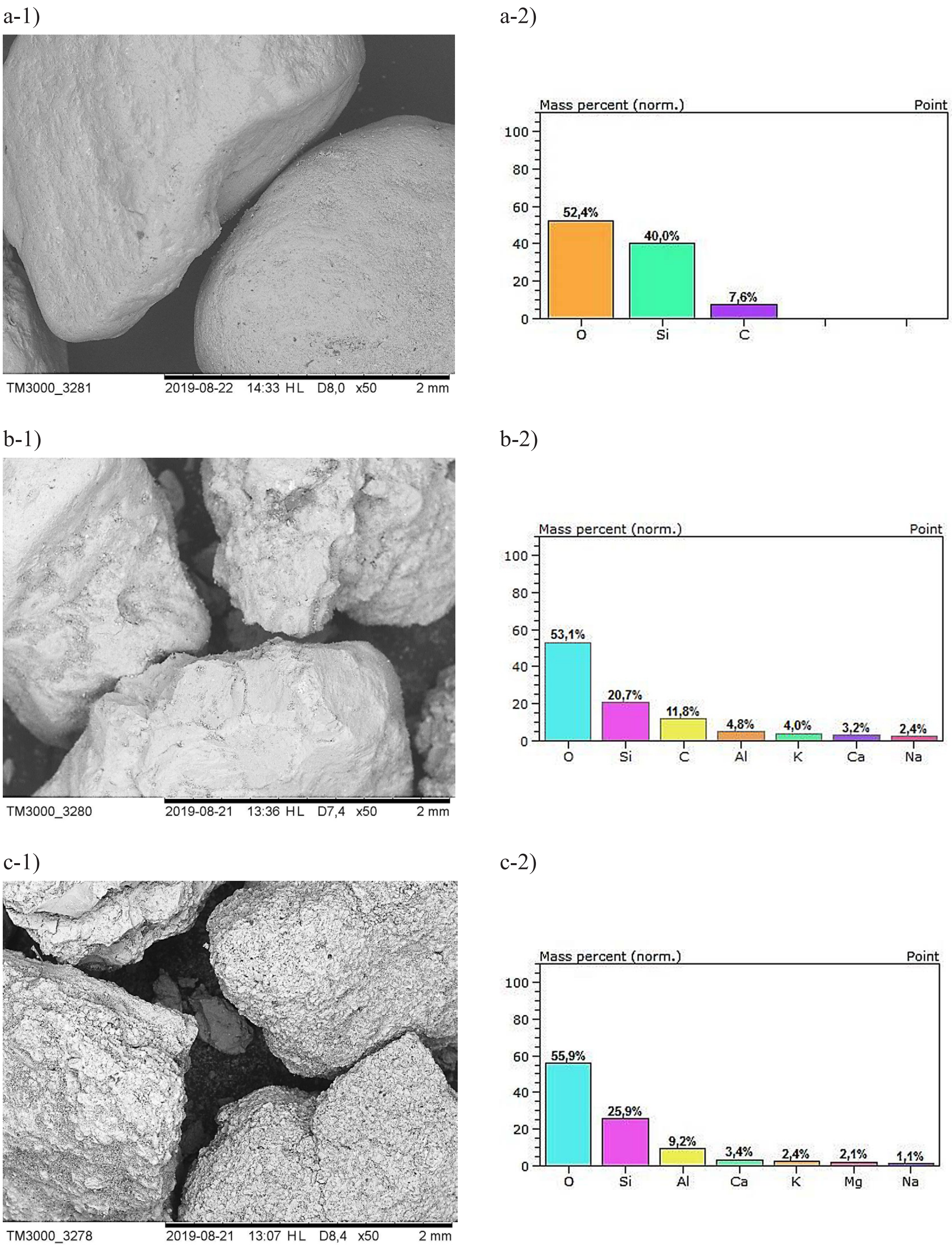
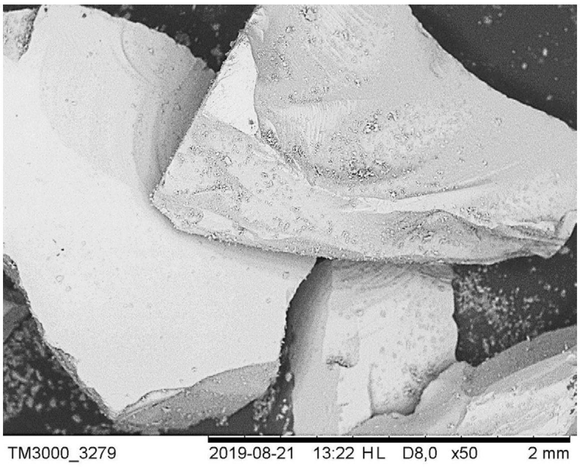
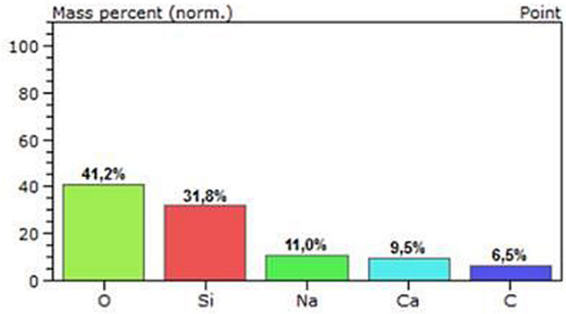


Figure 2. Image of aggregate grains magnified 50x and elemental composition; a) Grains of natural sand, b) Grains of ground waste concrete, c) Grains of ground waste ceramic

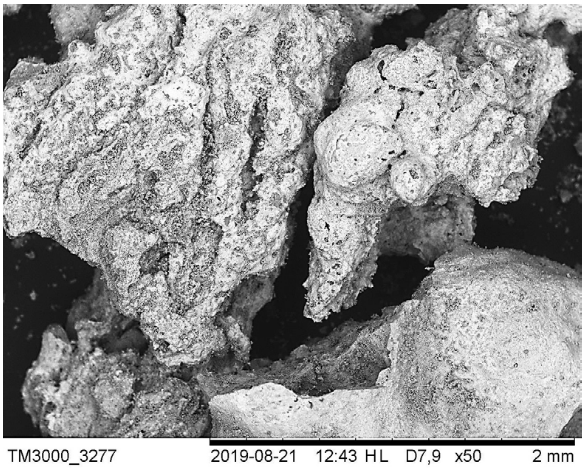
d-1)



d-2)



e-1)



e-2)

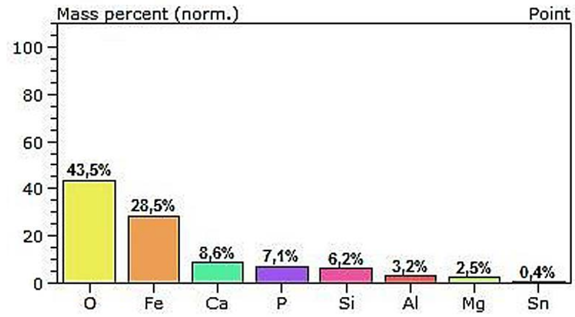


Figure 2, cont. Image of aggregate grains magnified 50x and elemental composition: d) Grains of waste glass, e) Grains of incinerated sewage sludge

cullet for this study was acquired from colored glass containers. The compound analysis of the waste glass shows that besides base feedstock compounds (SiO_2, Na_2CO_3, $CaCO_3$, dolomites, which include $MgCO_3 \cdot CaCO_3$) there are small insignificant fractions of glass dye. Ceramic and concrete waste grains have a similar composition to the initial material. The greatest difference is visible for the incinerated sewage sludge. Defined in Journal of Laws of 1st August 2019, no. 1437, on announcing the consolidated text of Act on collective provision of water and collective sewage disposal, urban waste water means "domestic waste water or the mixture of domestic waste water with industrial waste water and/or run-off rain water discharged by means of municipal sewage system". The composition of the waste water depends on the type of sewage. Recycling of such mixture by incinerating requires thorough inspections and quality control of its composition. Several harmful elements such as Pb, Cd, Hg, Cu, Ag, Bi, Tl, Th and U can be found in ordinary sewage, but due to production process of fine grade sewage sludge, the aggregate is free from them.

PROPERTIES OF CEMENT MORTARS WITH WASTE AGGREGATE

The mortars with milled cullet have already been studied for several years. The results of those studies can be found for instance in [Sikora et al., 2016, Skoczylas and Rucińska, 2018]. The properties of mortars with waste glass aggregate were left out in this study.

In order to determine the influence of waste aggregates, the grading curve was made to fit the

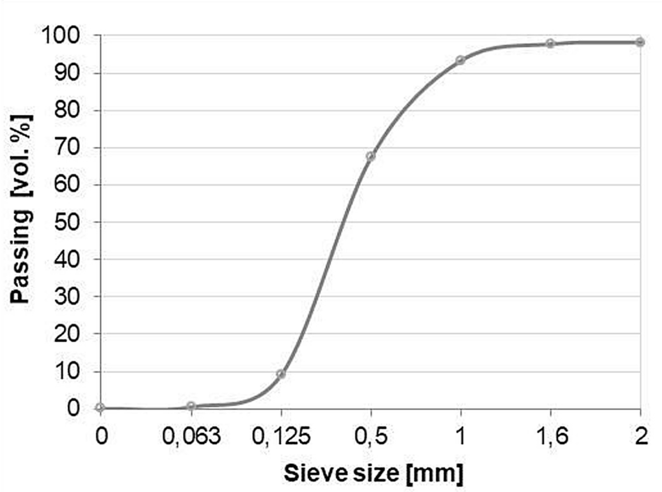


Figure 3. Natural sand grain size curve [Strzałkowski and Garbalińska, 2018]

curve presented in Figure 3. The mortars were prepared by replacing 10%, 20% or 30% of natural aggregate with waste aggregate.

The results of the study were compared to an ordinary mortar with 1:3:0.5 cement-aggregate-water ratio. The following mortars were prepared: RB10, RB20, RB30 with concrete waste, RC10, RC20, RC30 with ceramic waste and RO10, RO20, RO30 with incinerated sewage sludge. Table 2 contains the determined characteristics for the prepared mortars.

The results presented in Table 2 show that the mortar with 10% of waste concrete aggregate had similar properties as the reference mortar. An increase in the recycled aggregate volume results in the lowered parameters of the mortar. The use of ceramic aggregate decreases the overall strength of the mortars and increases their water absorption, but improves the thermal characteristics. The thermal conductivity of mortars with 30% ceramic aggregate decreased almost by 30%. The mortars with incinerated sewage sludge exhibit highest drops in total strength. However, the thermal properties were improved. Replacing natural aggregate with 30% of incinerated sewage sludge lowered the thermal conductivity coefficient by almost a half compared to the reference mortar. The thermal conductivity coefficient was determined for the dry state. Exposing the mortar to humidity can result in a deterioration of the parameter [Siwińska and Garbalińska, 2011]. The incinerated sewage sludge decreases the overall bulk density of mortars, due to the high porosity of aggregates. The aggregate also exhibited the highest water absorption. To conclude, the mortars with incinerated sewage sludge cannot be applied in high humidity environment and cannot be exposed to a direct contact with water.

Table 2. Properties of tested mortars

Properties	Sample designation									
	R	RB10	RB20	RB30	RC10	RC20	RC30	RO10	RO20	RO30
Volume density in dry state ρ_{dry} [kg/m^3]	2070	2020	1990	1960	2020	1940	1900	1970	1860	1780
$\rho_{dry,Rx}$/ $\rho_{dry,R}$ [%]	100	97.6	96.1	94.7	97.6	93.7	91.8	95.2	89.9	86.0
Flexural strength, after 28 days of maturation [MPa]	6.5	6.6	6.3	6.2	6.6	6.2	5.9	5.9	4.6	4.3
$f_{fs,Rx}/f_{fs,R}$ [%]	100	101.5	96.9	95.4	101.5	95.4	90.8	90.8	70.8	66.2
Compressive strength after 28 days of maturation [MPa]	47.2	44.1	43.0	40.8	45.5	41.3	34.4	42.0	33.9	28.7
$f_{cs,Rx}/f_{cs,R}$ [%]	100	93.4	91.1	86.4	96.4	87.5	72.9	89.0	71.8	60.8
Water absorption [%]	7.26	7.28	7.35	8.53	7.46	8.49	9.90	9.45	12.44	14.46
$W_{ab,Rx}/W_{ab,R}$ [%]	100	100.3	101.2	117.5	102.8	116.9	136.4	130.2	171.4	199.2
Thermal conductivity in dry state [W/(m·K)]	1.79	1.64	1.50	1.44	1.54	1.35	1.29	1.57	1.23	0.93
λ_{Rx}/λ_R [%]	100	91.6	83.8	80.4	86.0	75.4	72.1	87.7	68.7	52.0

The changes caused by the replacement of natural sand with recycled aggregate can be both viewed as beneficial or disadvantageous. Considering the entries in EN 998-1 and EN 998-2, the mortars with recycled aggregates can be considered as masonry or plastering mortars. Those mortars can successfully be used an alternative for standard masonry mortars. The applied recycled aggregate can also be used as a replacement of natural sand.

CONCLUSION

The discussed fine-grain aggregates obtained in the process of grinding waste material can be successfully used as a substitute for natural aggregate in the composition of cement mortars. According to EN 998–2 and EN 998–1, they can be qualified primarily for the masonry mortars. The thermal conductivity coefficient obtained in the test, which is on average about 30% lower in relation to mortar with sand, has a positive effect on the reduction of thermal bridges in the wall elements-mortar connection area. However, it should be noted that in the case of mortar with 30% slag obtained from the incineration of municipal sewage sludge, the thermal conductivity coefficient decreased even by about 50%. Despite the lower volume density of the mortars with waste aggregate, which is the result of the porous structure of grains of this type of aggregate, a significant decrease in the compressive strength was observed only with the share of 30% recyclate in relation to 100% of the volume of aggregate.

The tested mortars achieved the compressive strength above 30 MPa, while the mortar with 30% by volume of slag (from municipal sewage sludge) reached the value of 28.7 MPa. This allows all considered mortars to be classified as Md in terms of compressive strength, which indicates a guaranteed compressive strength of at least 25 MPa.

To sum up, it was stated that the described fine-grained waste aggregates can be used in the production of building mortars, guaranteeing obtaining technical values at the level specified in the standards for mortars, floor screeds or plasters, with particular regard to the environmental conditions under which they will be used, because high water absorption determines the limitation of the use of these mortars in an environment with increased relative humidity.

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