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PROPERTIES OF DEVELOPED SYNTHETIC LIGHTWEIGHT AGGREGATE (COMPOSITE) BASED ON HYDRAULIC BINDERS AND WASTE

Lightweight aggregates developed on the basis of hydraulic binders and mining waste were investigated in the study. Original technology was utilized to obtain the aggregates. The synthetic aggregate materials obtained in the work satisfy the basic requirements for materials used in construction. Granulates were obtained by granulating raw materials with a counter-current high intensity mixer having a nominal capacity of 30 litres. A rotary tube furnace was selected as the most appropriate to sinter the produced granulates. The process combined two operations: burning the combustible fractions (sewage sludge) responsible for porosity, and sintering (consolidating) the granulate. The sintering process was conducted at the temperature of 950°C in the presence of air. The working reactor tilt was about 2°. Initially the rotational speed for the quick tests was 4.28 rpm, which yielded a granule residence time of about 7.3 minutes in the heating zone (a variant was applied for the tests). The obtained aggregates were subjected to strength testing, and their crushing resistance was determined based on standard PN-EN 13055-1. Depending on the proportions of the individual raw materials, the aggregates are characterised by high crushing resistance from 4.1 to 6.5 MPa, which confirms the potential for their industrial application. These aggregates may be used for purposes such as lightweight building and pavement concrete production due to their relatively low bulk density.

Keywords: sewage sludge, synthetic lightweight aggregate, granulates

INTRODUCTION

Lightweight aggregates (LWA) are construction materials with a lower bulk density than standard construction aggregates. The microstructure of LWA has an influence on the properties of the aggregate such as the density, absorbability and strength, which is proportional to its influence on concrete. The microstructure of the aggregate is influenced by the applied raw materials and methods of hardening [1]. Sintering and cold bonding are the two most common methods for producing synthetic LWA. Sintering is a method for altering the structure and density of materials without melting them to the point of liquefaction by means of heat or pressure [2], whereas cold bonding utilises various kinds of binders, including hydraulic and synthetic agents. Subjecting the input material to chemical processing and preserving it in acidic or basic conditions may also have a significant influence on the final properties of the aggregate [3].

Some of the current major challenges in waste management include recycling, protecting limited natural resources, as well as reducing energy consumption and greenhouse gas emissions. The use of natural aggregates by the construction material industry ranges from 8 to 12 billion tons a year [4]. In the context of sustainable ecological development, reducing the amount of cement for the production of concrete and increasing the contribution of synthetic aggregates in the said production is of great importance and priority [5]. Involving industry in the circular economy has become a significant challenge in recent years. Among others, the zinc and lead sectors are struggling with major problems related to the management of enormous quantities of produced waste. The generated slag constitutes an environmental problem both with regard to the necessity for its storage and the potential release of contaminants to the soil and water environment. A solution to this is the appropriate processing of waste and granting it useful properties with the simultaneous prevention of its negative impact on the environment. The purpose of this paper is to analyse the properties of a lightweight aggregate developed based on the Central Mining Institute's technology, protected by a patent, Pat. 238116, which may constitute an attractive substitute for materials of natural origin [6].

MATERIALS AND METHODS

The conducted work involved studies intended to produce granulates obtained by granulating raw materials with a counter-current high intensity mixer. The studies included mixing intensity testing, rotor and pan rotational speed selection, and determination of the time required for granulation. The granulates for further investigations were prepared by means of a mixer with a nominal capacity of 30 litres. The setup used to obtain the granulates is presented in Figure 1.

Fig. 1. Counter-current high intensity mixer used for the studies (Ideapro, Nowa Sól, Pl)

During the processing of the researched materials, the mixer was equipped with a star belt agitator. The structure of this agitator enables the disintegration and fragmentation of agglomerated raw materials. The high linear velocities of the agitator in the utilised mixer, to a level of 20 m/s, made it possible to conduct this stage of the work by setting the pan and agitator to a counter-current mode of operation. The next step of the process was homogenisation, ensuring a uniform mixture composition in the entire feed volume and its granulation in the final stage.

The granulated samples were sintered in a Czylok (Poland) PRS 150x150/110/OBR rotary tube furnace. The basic technical parameters of the furnace include:

- maximum operating temperature – 1100°C
- three heating zones
- heating zone length – 1500 mm
- internal diameter – 150 mm.

The furnace is equipped with a three-zone heater and a horizontal reactor. Each heating zone is equipped with a separate heating controller and features a heating power of 6 kW (a total power of 18.5 kW). The utilised furnace is presented in Figure 2.

The rotary tube furnace was selected as the most appropriate for the experiment. It makes it possible to conduct the process in a continuous manner (similar to industrial conditions), without stopping the stock feed or product collection. Such a solution makes it possible to obtain process conditions that are stable and constant over time. This type of furnace enables constant atmosphere control as well as its alteration in real time, if necessary. The ease of discharging reaction gases affecting the course of the sintering process also has a significant influence on the selection of the furnace type. Another benefit is the ease of critical process parameter control and variation during the process itself.

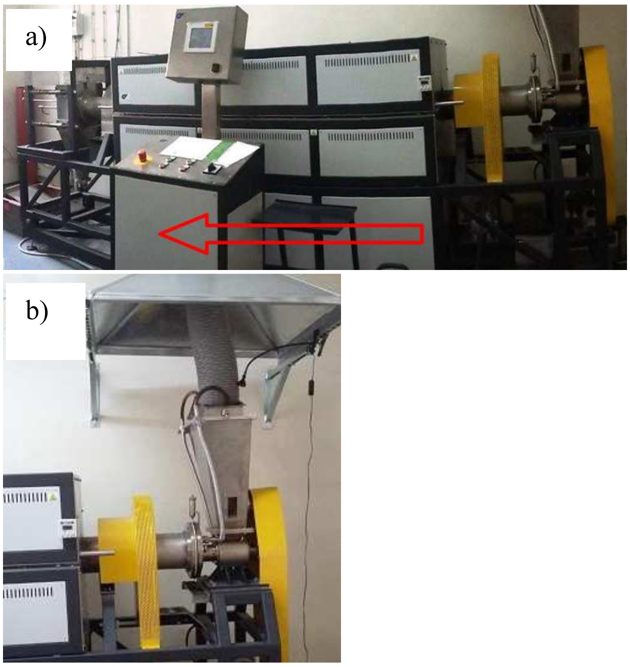

Fig. 2. Photographs of: a) rotary tube furnace, b) automatic screw feeder

Generally, the process combined two operations: burning the combustible fractions (sewage sludge) responsible for porosity, and sintering (consolidating) the granulate. Sludge burning is a strongly exothermic process (spontaneous local rising of the furnace is possible) at the beginning of the working zone, when the heat exceeds the ignition temperature. The process is accompanied by intense combustion gas emissions that must be removed from the working zone as they limit oxygen access and thereby hinder the sintering process. It should, however, be remembered that too quick combustion gas removal may result in a too great oxygen inflow and an increase in temperature. The actual sintering of the granules occurs only in the remaining part of the reactor. Therefore, the possibility of selective individual heating zone parameter control is of key importance to enable the process to be conducted correctly. In the sintering of this type of granules, the total number of granules is subjected to the process simultaneously. The time and temperature of combustible fraction burning (furnace zone 1), the time and temperature of individual granule sintering (working zone 2 and 3) as well as the rotational speed of the reactor, the working tilt, atmosphere, the method and volume of air supply to the process, the method of combustion gas removal, and the method and rate of product cooling must be selected in such a way that the combustible components may be burnt first before the material is sintered. Ignoring the order of the processes may significantly increase the process time and cost, as well as impact the final product properties. Thus, conducting the process appropriately necessitates the correct (often experimental) selection of all the relevant parameters.

The furnace reactor consists of a 159 x 6.3 mm tube formed from heat resistant steel (type 1.4841 – X15CrNiSi25-21) with a length of 3000 mm. Inside the reactor tube, over the entire length is a corrugation formed from an 8 mm heat resistant bar with a pitch of 48 mm (distance between the coils of 40 mm). The reactor is mounted on supports and driven by a gear-motor with a gear ratio of 62 via a chain transmission (chain 12B) with a gear ratio of 0.267. The reactor rotational speed at a nominal motor rotational speed is 3.74 rpm, which at a corrugation pitch of 48 mm yields a material residence time of about 120 minutes. The range of gear-motor control is within 25-110% of the nominal motor rational speed, i.e. from 0.935 to 4.11 reactor rotations per minute. The reactor is sealed with Teflon face gaskets, while constant pressure is achieved by means of a spring assembly mounted on the unit collecting the sintered material. The tilt of the furnace, reactor and other working elements relative to the base is regulated within an angle range of 0 to 4°. Tilting is accomplished by means of a hydraulic system consisting of a water seal and a position lock mounted on the charging side (charging hopper).

During sintering, the raw material is fed to the working reactor by means of an automatic screw feeder (Fig. 2b). The primary working element of the feeder is an auger with a working diameter of 60 mm and a pitch of 40 mm, driven by an MRA 40 gear-motor with a gear ratio of 64 via a chain transmission (chain 8B) with a gear ratio of 0.217 (z1 = 60, z2 = 13); the feeder is equipped with a reinforced connection to the reactor that simultaneously constitutes the basis of the entire reactor system with process gas conduits. The feeder tank is in a hopper with a volume of 18 dm^3, formed entirely from stainless materials, with an installed stock agitator driven via a chain transmission by means of a screwdriver. The tank is equipped with a feeding port for loading the stock, sealed with a quick-clamp silicon gasket. At the operator's side is a round sight glass for observing the sidewall loading level.

The product collection assembly at the end of the working reactor consists of a collection chamber in the form of a funnel that is suspended in the reactor, with a mounted reactor coupling tube. All these elements are formed from stainless steel. The chamber is pressed to the reactor by a system of 4 springs. A detachable flange is mounted on the wall opposite the inlet to grant access to the reactor and collection tank. The flange includes two 25 mm visors, a gas discharge port and a measuring thermocouple socket for temperature measurements in the second and third furnace reactor working chamber heating zones. Figure 3 presents a view of the sintered granules during sintering.

The sintering process was conducted at the temperature of 950°C in the presence of air. The working reactor tilt was about 2°. Initially, the rotational speed for the quick tests was 4.28 rpm, which yielded a granule residence time of about 7.3 minutes in the heating zone (a variant was applied for the tests). The high reactor speed and the presence of numerous granules in the heating zone resulted in intense burning of the combustible fractions. A rapid temperature increase at the feeder was observed, with a real risk of granulate ignition in the feeder. This phenomenon also led to an uncontrolled temperature increase inside the reactor, which posed a risk of losing control over the process.

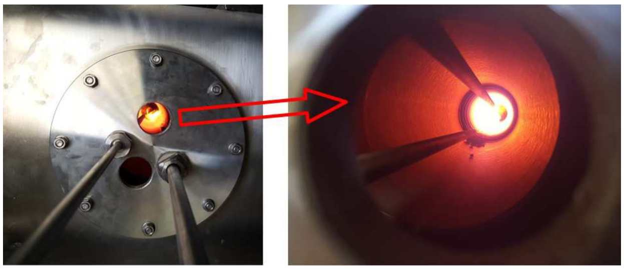

Fig. 3. Sight glass in furnace flange showing sintered granules during sintering

The granules obtained in the quick test had a heterogeneous internal morphology, clearly exhibiting unburned components (light outer edge, darker inner areas). To improve the granulate parameters, the granulate feeding rate to the reactor (the quantity of granulate fed in a unit of time) was reduced together with a decrease in the reactor rotational speed to 2.15 rpm, which at the corrugation pitch of 48 mm doubled the residence time in the furnace heating zone to about 14.5 minutes. This made it possible to avoid the uncontrolled temperature increase by conducting a less dynamic sintering process, while yielding a more homogeneous internal granule structure (grey colour).

SINTERED GRANULATE CRUSHING RESISTANCE TEST

Aggregates exhibiting properties appropriate for lightweight aggregates were obtained from the raw granulates by the sintering process. The bulk density of the obtained aggregates (for 4-10 mm fractions) is provided in Table 1.

TABLE 1. **Obtained aggregate bulk density**

Aggregate	**[kg/m^3]**
KR1	716
KR2	723
KR3	699
KR4	713
KR5	696
KR6	712
KR7	653
KR8	669
KR9	761

The obtained aggregates were subjected to strength testing, and their crushing resistance was determined based on standard PN-EN 13055-1. The purpose of the strength testing was to determine the properties of the granules after heat treatment at various sewage sludge, clay and ash contributions in the mixture. The tests were conducted at various contributions of individual components in the granulates. Three crushing resistance test samples were prepared from each obtained aggregate. According to the aforementioned standard, crushing resistance tests may be carried out for aggregates with a size range of 4 to 22 mm and a bulk density greater than 150 kg/m^3. Thus, the fractions under 4 mm and over 10 mm were removed from the prepared individual aggregate test samples in order to provide more uniform samples for comparative tests. The aggregates obtained by sintering were characterised by a varied content of fractions greater than 10 mm. Individual large granules in the tested material volume could have resulted in false readings of the force necessary to achieve the appropriate piston compression in the studied material as per the standard. The researched aggregates were subjected to mechanical testing consisting in uniaxial granulate compression in the steel cylinder of an INSTRON 4469 testing machine (Instron, Norwood, MA, USA) with a maximum force of 10 kN.

Crushing resistance C_a of individual aggregates was calculated based on the following equation:

$$C_a = \frac{L + F}{A} \left[\frac{\mathrm{N}}{\mathrm{mm}^2}\right]$$

where: C_a – crushing resistance in Newtons per square millimetre [MPa], L – force exerted by the piston, in Newtons, F – force required to press the piston, in Newtons, A – piston surface area, in square millimetres.

The crushing resistance of the individual investigated synthetic aggregates was determined based on the conducted tests (three samples per aggregate). The measurement results are depicted in Figure 4. Furthermore, Table 2 presents the individual granulate compositions in w/w%.

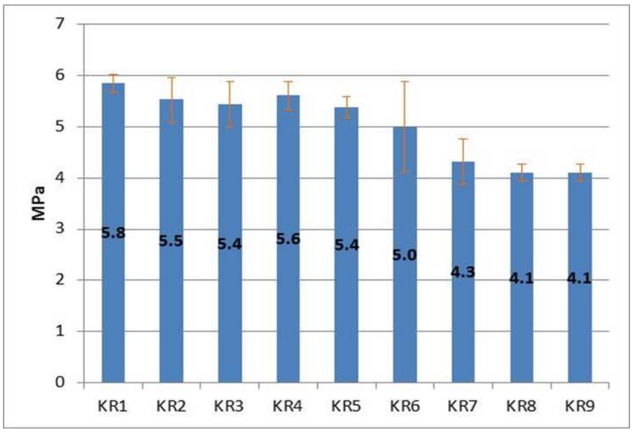

Fig. 4. Crushing resistance of studied aggregate; where: KSP8' – sample sintered over a shorter time

TABLE 2. **Compositions of studied material variants in w/w%**

w/w%	KR1	KR2	KR3	KR4	KR5	KR6	KR7	KR8	KR9
Clay	40	30	40	30	40	30	40	30	50
Sewage sludge	20	30	30	40	40	50	50	60	50
Ash	40	40	30	30	20	20	10	10	0

The obtained aggregate crushing resistance ranges from 5.8 to 4.1 MPa. It can be observed that the aggregate resistance increases together with the increase in clay content and the decrease in sewage sludge in the investigated aggregate compositions. The aggregates produced from clay or containing predominantly clay are characterised by the greatest strength due to their most compact structure, as confirmed by the bulk density tests of the individual aggregates. The aggregates with the greatest clay content are characterised by the highest bulk density. Most likely, these aggregates also exhibit the lowest porosity compared to the those produced primarily from sewage sludge. The key parameter determining the sintered material strength in this case was probably the sewage sludge content owing to the generation and release of the greatest quantity of gaseous components during granulate sintering, and an increase in porosity as a result, which is confirmed by the lowest bulk density of the sintered products obtained from granules with the greatest sewage sludge content.

In the case of sewage sludge, which is a waste material currently without common use in industrial processes, it can also find effective application in synthetic aggregate production. It must only be considered what level of aggregate strength and porosity is desired. The obtained strength test results suggest a fairly broad spectrum of possible individual waste material contributions in the raw material volume for synthetic aggregate production. The key parameter limiting the possibility of utilising individual raw materials may be the degree of their contamination and the likelihood of introducing harmful substances (of various character) into the aggregate, with a negative influence on the material properties such as leachability or environmental migration etc.

In analysing the obtained test results, it can also be concluded that the ash and its content have a significant influence on the strength properties of the produced aggregates. It is acknowledged that ash has a positive effect on the sintering process, intensifying it depending on the sintering temperature. Based on the obtained results and the individual aggregate compositions, it can be clearly determined to what degree the ash content in the aggregates influences their strength properties at a given sintering temperature of the analysed granulates. In the investigated granulates, the ash content ranged from 0 to 40 w/w%. Based on the environmental perspective, and the fact that ash is a critical additive to achieve the correct granulate formation process, its inclusion makes it possible to obtain the appropriate level of granulation mixture moisture, while its addition in the final stage of granulation has further beneficial effects. Its application in greater quantities is valid both from the perspective of the process and the environment.

To summarise the strength test results, it should be noted that the obtained aggregate strength is significantly higher compared to most aggregates available on the market. The crushing resistances of example commercial aggregates include:

- Liapor – 0.7-10 MPa
- Arlita – 0.98 MPa
- Lytag – 0.43 MPa
- LECA and Ardelite – 0.09 MPa
- Geokeramzyt Matrix – 0.8 MPa
- LECA Gniew – 0.7-4.0 MPa

For comparative purposes, the resistance test results of the analysed synthetic aggregates produced in a mixer with a nominal capacity of 600 litres at a semi-industrial scale are presented in Figure 5, with their compositions displayed in Table 3.

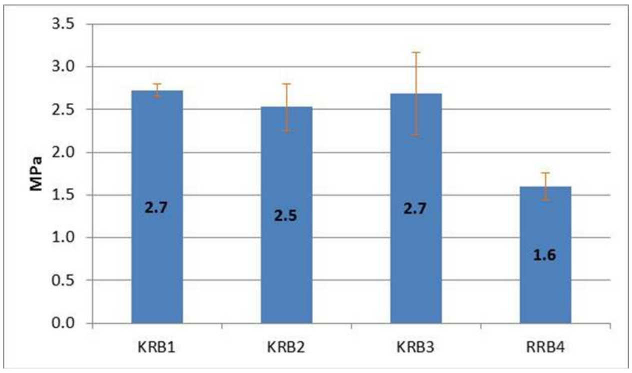

Fig. 5. Tested aggregate crushing resistance

TABLE 3. **Studied material variant compositions in large-scale tests**

Designation \ Raw material	Clay	Sewage sludge	Fly ash	Quicklime
	Contribution in mixture		Addition to clay and sludge mixture [w/w%]	
KRB1	1	1	10	0
KRB2	1	1	10	5
KRB3	1	1	20	0
KRB4	1	1	0	0

In all the analysed material variants in the laboratory tests, the clay-sludge relation was the same and amounted to 1:1. Quicklime was added to individual mixtures in the amount of 5 w/w%, as well as fly ash in amounts of 10 and 20 w/w%. Analysing the obtained test results makes it possible to conclude that the quicklime additions result in decreased strength properties of the researched aggregates.

CONCLUSIONS

The conducted investigations of the obtained materials in the form of lightweight aggregates demonstrated that the by-products of limestone aggregate washing such as sewage sludge or clay, as well as combustion by-products in the form of ash, can be used as raw materials for lightweight aggregate production.

The synthetic aggregate materials obtained over the course of the work satisfy the basic requirements for materials used in construction. Depending on the proportions of the individual raw materials, the aggregates are characterised by high crushing resistance from 4.1 to 6.5 MPa, which confirms the potential for their industrial application. These aggregates may be used for purposes such as lightweight building and pavement concrete production due to their relatively low bulk density.

This work contributes to the increasingly popular idea of circular economy, which makes studies of this type all the more valid and promising.

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