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Design of a mixture for construction purposes using secondary energy products

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Abstract: The article deals with research into the possibilities of creating a material that would be a combination of SEP with alkali-activated systems, which today are referred to as geopolymers. SEPs are secondary energy wastes, which are referred to as fly ash, slag and products of flue gas desulfurization technology. Geopolymers are complex composites whose binder component consists of aluminosilicates in combination with alkaline activators.

Keywords: fly ash, slag, geopolymer

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Introduction

There is currently a high production of secondary energy products (SEP). These types of waste are referred to as ash, slag and products of flue gas desulfurization technology. In particular, around 10 million tonnes of fly ash are produced in the Czech Republic in the production of electricity.

Ash is a heterogeneous material whose chemical, physical and technological properties depend on the quality of the coal burned and also on the technology of the combustion process itself. The fly ash composition consists of 50 % silica, 25-35 %

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alumina and between 3-8 % FeO. Ti, Ca, Mg, Na and K oxides also appear in very small quantities (Enviweb, 2004). Ash is a product of burning powdered anthracite, black or brown coal and it is used in the production of concrete or concrete products. Ash is used as a substitute for natural raw materials in road construction and it is also used in the production of asphalt products or mortars. Furthermore, it is a suitable raw material for the creation of geopolymers (Cezep, 2020; Sanytsky et al., 2020).

Another type of SEP is slag, which is divided into several types. There is blast furnace slag, steel slag and also power plant slag. Slag production in the Czech Republic is around 1.5 million to 2 million tons. The majority of slag is produced from power plants. It is mainly used in the field of artificial aggregates or in the production of slag cement. The slag is cooled by water when it exits the furnace resulting in the formation of a slag granulate, which is further processed by milling and has good pozzolanic properties (pozzolanic activity is the ability to react with $Ca(OH)_2$, thus determining binding properties), it is suitable for cement production. Slag cement is already known all over the world and is widely used. In this cement, the blast furnace granulated slag gives the cement higher chemical resistance and positively affects the long-term properties of the concrete. (Matějka, 2010; Trejbal et al., 2016).

The reason for the presented research is the effort to create a material that would be a combination of VEPs with alkali-activated systems, which today are referred to as geopolymers. This would make it possible to further increase the recycling possibilities of these wastes. Geopolymers are complex composites whose binder component consists of aluminosilicates in combination with alkaline activators. Great interest in the research of geopolymers has appeared in the last 20 years, but the beginning of their creation can be dated back to ancient times. Geopolymers have found their use, for example, in the construction industry in the production of tiles, sleepers, breakwaters, sewage structures, etc. They are also able to immobilize toxic waste (Davidovits, 2006; Van Jaarsveld et al., 1998).

As part of our research, the newly created material could find application in the construction industry, e.g. in the creation of curbs, bricks, facings, paving, etc. As already mentioned, geopolymers are already used in the field of construction, but our idea is to supplement the materials created in this way with a filler, which would greatly improve the mechanical properties and thus be equal to today's widely used materials such as concrete. Concrete is a composite building material. The binder of this material is Portland cement and aggregate as a filler. The biggest problem with concrete is its carbon balance, due to cement. Of the total global emissions of carbon dioxide, cement includes a full 8 %, which puts the construction sector in a higher position than e.g. air transport in terms of polluting activities (Dohnal, 2021).

1. Materials

First, it is necessary to get a closer look at the materials that were dealt with in the research.

1.1. Geopolymers, history and concept

Probably the first use of geopolymers can be found already in ancient times. According to the theory of Davidovits, who stated in the 1980s, a certain type of geopolymer was already used during the construction of the pyramids. For these constructions, the geopolymer was poured directly into wooden forms placed directly in the construction, instead of pulling already pre-formed blocks directly to the construction sites of the pyramids. This theory is confirmed by the fact that the blocks in the pyramids are perfectly accurate in terms of dimensions. Such precision could not be sustained if every single block was produced in a different place. Davidovits therefore, believes that a mixture of ancient concrete (geopolymer) was poured into the molds. This was made from crushed limestone, clay, water, lime and a highly alkaline activator. It was the alkaline activator that reconstituted the mixture into an artificial stone (Davidovits, 2006).

The first half of the 20th century saw one of the first major applications of alkali-activated materials, or geopolymers. Such an application was used in 1934 at the ceramic company Olsen. Here, the application of a mixture based on kaolin and sodium carbonate appeared for the first time. At the same time, in these years there was research into the combination of sodium and potassium hydroxide with blast furnace slag as an additive to Portland cements. Scientist Purdon was responsible for this, thanks to which new fast-hardening binders were discovered.

In the 1950s, there was research into geopolymers by the US military in which ground slag and sodium chloride and sodium hydroxide were mixed. In these years, alkali-activated slag cements were also used in the construction of structures. Prof. Glukhovsky, who described the creation of ground cements in his book, made the greatest contribution in the 1950s. These are concretes created by alkaline activation of slag. His book is titled Grunt Silicates. Based on the research of prof. Glukhovsky, one building was built on the territory of Ukraine from blocks created according to his recipe.

The greatest contribution to geopolymers can be attributed to Davidovits, who in the 1970s, together with a team of scientists, prepared a mixture for the production of waterproof ceramic tiles that did not have to be fired. The main milestone in the research of Davidovits was the description of geopolymerization and the subsequent naming of alkaline-activated materials as geopolymers.

As for the research of geopolymers in the Czech Republic, since the 1960s, it was prof. Brandšter from VUT in Brno. His work was also followed up by scientists from CVUT and VŠCHT in Prague. They have been engaged in this research since the first half of the 70s. In 1979, they succeeded in formulating the principles of preparation without gypsum Portland cement. Thanks to the formulation of principles for preparation, so-called BS cement was created, which was subsequently applied to industrially produced building materials. BS cement consists of Portland cement or slag, alkaline salt and anionic surfactant. Thanks to the procedures in their research in the following years, POPconcrete was created. POPconcrete is a geopolymer cement-free concrete based on fly ash, which reaches a compressive strength of up to 60 MPa. To this day, this material is still being innovated.

Institutes, such as the Institute of Industrial Ceramics FMMI VŠB – TUO and the Institute of Rock Structure and Mechanics AVČR in Prague, are also engaged in research into geopolymers using slag or fly ash. Since 2004, the Czech Development Agency has also been involved in the field of geopolymer research. Its main goal is to promote technologies, support research and introduce geopolymers into construction practice (Boháčová et al., 2012).

Professor Davidovits introduced the term "geopolymer" in 1978. The so-called materials are inorganic polymers obtained by alkaline activation of aluminosilicate materials. The reason for the development of inorganic polymers was several fire events in the 70s throughout Europe. Therefore, Davidovits decided to find a fire-resistant alternative to the organic polymers of the time.

The structure of geopolymers can be defined as covalently bonded non-crystalline Si-O-Al networks in which SiO_4 and AlO_4 tetrahedral structures are connected with shared oxygen. These structures create amorphous to semi-crystalline 3D structures. Such structures are called geological polymers for the reason that their starting raw materials for creation are of geological origin. The formation of these geopolymers takes place through inorganic polymerization and condensation reactions. Their structure is therefore very similar to natural zeolites thanks to Si-O-Al bonds.

Considering the publications published so far, we can characterize geopolymers by the following points (Škvára, 2007):

- they do not contain a uniform structure of the polysialate-siloxo type,
- they contain pore water and gel,
- they have a porous structure,
- water is the carrier of the alkaline activator,
- crystalline and amorphous hydrates are only rarely present when slag or calcium-containing material is present in the mix,
- they have a random arrangement of 3D structure.

Geopolymers have the potential to replace conventional Portland cement, and even overcome its manufacturing limitations. As Portland cement requires high temperatures for the calcination process, greenhouse gas CO_2 is produced during this production. However, in the production of geopolymers, this fact does not occur, so it is an ecologically suitable alternative for the future.

1.2. SEPs

Secondary energy products (SEPs), as already mentioned above, are fly ash, slag and products of flue gas technology. These products are created when coal is burned in power plants. The use of these waste materials provides both economic and environmental benefits.

1.2.1. Slags

Slags are by-products (secondary products) of metallurgical production and belong to important alternative sources replacing natural raw materials. In general, there are 3 types of slag, the first type is steel slag, the second type is blast furnace slag, and the last type are non-ferrous slags and phosphorus production slags (Cezep, 2020).

Steel slag is again divided into 3 types:
- steelmaking slag BOF – alkaline steelmaking slag (most older steelmaking slags),
- converter slag LD (slag from converters),
- EAF steel slag (electric furnace slag).

Steel slag is not used at all as an aggregate for concrete. The reason is primarily concerned with slow and long-term decay and volume changes. Hydration of free lime (CaO), hydration of pericase (MgO), carbonation of calcium and magnesium hydroxides, polymorphic transformation of dicalcium silicates and reactions of aluminates contribute to these changes. All reactions associated with slag hydration or decomposition are also affected by the presence of a glassy phase that easily breaks down and contributes to volume changes. In the literature, it is agreed that the use of steel slag in construction practice is problematic and is only possible if all laboratory tests are carried out properly and if the quality of the slag excluding volume changes is proven (Kalina, 2011).

Blast furnace slag is produced from waste melt during the production of iron in blast furnaces. If this slag cools slowly in the air, a hydraulically inactive material is formed, which remains constant in volume, and after crushing and sorting, it is used as a common backfill material on road constructions. In the past, especially in Ostrava, it was also used as an artificial aggregate for the production of concrete. If the hot blast furnace melt is rapidly cooled by a stream of pressurized water, a granulated slag with grains of approx. 5 mm in size with deep open pores is formed. In the past, it was sometimes used as a lightweight concrete filler. Usually, however, granulated slag is finely ground and used as a desired latently hydraulic admixture, either separately dosed during the production of concrete, or more often as the main component of mixed cements. Its hydraulic activity determined after three months and later, which is expressed by the efficiency index, tends to be greater by 100 % compared to cement without slag. This type of slag is in great demand due to its permanent properties and as an admixture of mixed cements it has no problem with sales (Kalina, 2011).

1.2.2. Ashes

Another group of materials within the SEP are fly ashes. Fly ash is obtained from the combustion of powdered anthracite, black or brown coal in power plants. Ash can be coarser or finer, depending on the place from which it is separated from the flue gas. Coarse ash is obtained by gravity separation in the back drafts of the boiler. Finer fly ash is obtained from electrostatic precipitators. Nowadays, fly ash is generally used in the production of concrete, in brick production, in the production of cements, putties and artificial aggregates (Cezep, 2020).

As part of the issue, a distinction is made between high-temperature fly ash and fluid fly ash.

High-temperature power plant ashes are non-combustible residues of pulverized coal combustion in thermal power plant boilers at temperatures of 1200-1700 °C. High-temperature ashes represent approximately 80 % of non-combustible residues. The most common method of removing ash from flue gas is using electrostatic precipitators. The chemical composition of the fly ashes are similar to natural pozzolans and, unlike cement, they have a significantly lower proportion of CaO.

Fluid ashes are produced during combustion in fluid hearths at a temperature of 850 °C. This combustion temperature is lower than the ash melting temperature, so there is no remelting of the ash particles and the grains remain porous. Alkaline additives are added to the combustion space, which is why the fly ash contains a high content of sulfur dioxide (SO_3 up to 30 %) and free lime (CaO up to 25 %). During combustion, two types of ash are produced, lodge ash and fly ash. The fly ash is carried away from the boiler together with the flue gas and is captured on electric separators. Lodge ash is a coarser fraction than fly ash. This is due to its formation when the heavier solid residues from combustion are not removed together with the flue gases, but are returned back to the boiler in the separator. From there, the lodge ash is drawn off to maintain a constant fluid bed of combustion. It is then cooled and stored in silos. Compared to fly ash, it also differs in its chemical composition, where lodge ash contains a higher proportion of free lime. Fluid fly ash is more reactive compared to high-temperature fly ash. The optimal dose of fly ash was determined by Balkovič et al. to 15-20 % replacement for the silicon component (Balkovic & Drábik, 2010; Fečko et al., 2003).

1.3. Selection of materials for the preparation of experiments

The very first step of the subject research was the selection of suitable raw materials and fillers for the production of geopolymer samples. Given the information based on literary sources (Ahmad, 2017; Davidovits, 2011; Dohnal, 2021; Duxon, 2007; Kobaka & Katzer, 2022; Popławski & Lelusz, 2018; Provis & Deventer, 2009; Vickers et al., 2015) dealing with this issue, the raw materials that are suitable for this research were determined.

Two main raw materials were chosen, which were subsequently incorporated into the recipes. These raw materials were slag and fly ash. Due to the fact that these raw materials are classified as secondary energy products and the potential of their use has not yet been fully fulfilled, they were chosen for the research in question.

The next step was the selection of fillers that would fulfil the assumption of improving the mechanical properties of the resulting material. Based on information from previous research (Vickers et al., 2015), glass fibers, basalt granulate, fittings and aggregate-based fillers were chosen as fillers.

Fig. 1. Power plant slag collection from the Počerady power plant (*own research*)

The collection of secondary energy products was carried out thanks to cooperation with the Počerady power plant on their land (Fig. 1).

The geopolymer binder was supplied and designed by the Academy of Sciences of the Czech Republic.

An overview of the raw materials used is summarized in Table 1.

Table 1. Overview of used raw materials (*own research*)

SEPs
• power plant fly ash • power plant slag
Binder for geopolymers
consists of: • water glass • metallurgical waste • glass waste
Fillers to improve material properties
• basalt granules (0.5-1 mm) • fiberglass (length 12 mm) • aggregate-based fillers: ✓ aggregate 0/4 – sand ✓ aggregate 4/8 – fine gravel

Basalt granulate and glass fibers should help to improve the mechanical properties of the resulting material. The basalt filler should provide an increase in fire resistance as well as strength. For fiberglass, there should be a significant improvement in flexural strength (Vickers et al., 2015).

1.4. Suspension proposal

In the second stage of the research, the goal was to determine the recipes of individual geopolymer suspensions. This is a mixture suitable for vibro-pressing, thanks to the vibro-pressing technology it is possible to produce building materials for commercial purposes. The recipes were divided into two basic groups, based on the secondary energy product used. Therefore, they are suspensions with the presence of ash or slag.

1.4.1. Suspension with fly ash

Suspensions with fly ash are based on the basic composition established on the basis of the recommendations of the staff of the Academy of Sciences of the Czech Republic based on their laboratory experiments. It consists of 3 basic components, geopolymer binder, fly ash (SEP) and water. Geopolymer binders consist of metallurgical wastes, water glass and glass wastes.

The designation of the individual components of the suspensions implemented was as follows:

- metallurgical waste = component A,
- water glass + glass waste = component B,
- fly ash = component C,
- geopolymer binder (2 components in a ratio of 1.4:1) = component G.

In Table 2, there is the composition of the trial suspension, which was created for testing the mixing of individual components based on fly ash.

The addition of individual components of the mixture has already been successfully tested in the initial suspension in the laboratories of the Academy of Sciences of the Czech Republic, and therefore it was also used in the creation of other suspensions.

Table 2. Composition of the trial suspension using fly ash (*own research*)

Component	Order of addition into suspension	Composition [%]
A	1	25
B	1	18
H_2O	2	27
C	3	30

In total, 12 formulations of fly ash suspensions were created. The designation of individual types of suspensions was:

- suspension with fly ash – reference composition,
- suspension with fly ash (A, B) + Plasticizer Den Braven (hereinafter only P) – desig. **1A**,
- suspension with fly ash (A, B) + P + basalt granulate – desig. **2A**,
- suspension with fly ash (A, B) + P + glass fibers – desig. **3A**,
- suspension with fly ash (A, B) + P + armature – desig. **4A**,
- suspension with fly ash (A, B) + P + reinforcement + basalt granulate – desig. **1B**,
- suspension with fly ash (A, B) + P + glass fibers + basalt granulate – desig. **2B**,
- suspension with fly ash (A, B) + P + aggregate 0/4 – desig. **1C**,
- suspension with fly ash (A, B) + P + aggregate 4/8 – desig. **2C**,
- suspension with fly ash (A, B) + P + aggregate 0/4 + 4/8 (2:1) – desig. **3C**,
- suspension with fly ash (G) + P + aggregate 0/4 – desig. **1D**,
- suspension with fly ash (G) + P + aggregate 4/8 – desig. **2D**
- suspension with fly ash (G) + P + aggregate 0/4 + 4/8 (2:1) – desig. **3D.**

As part of suspension with fly ash, four groups of suspensions were implemented. An improvement in the resulting mechanical properties of the material was expected. The first group was suspensions with a single-loop filler (Table 3). Individual data is always written one after the other and the value applies to them in the same place as in the cell above it. This means that, for example, component A in suspension

1A has representation in percentage composition 24.5 %, and in the mixing process it was inserted into the mixture first. In Table 3 are compositions of suspension with fly ash and with one type of filler.

Table 3. Suspension with fly ash and with one type of filler – composition (*own research*)

Suspension	**1A**	**2A**	**3A**	**4A**
Components	A; B; H_2O; C; P	A; B; H_2O; C; P; basalt granulate	A; B; H_2O; C; P; glass fibers	A; B; H_2O; C; P; armature
Composition [%]	24.5; 18; 26.2; 29.5; 1.8	23.4; 17.2; 25; 28.1; 1.6; 4.7	23.4; 17.2; 25; 28.1; 1.6, 4.7;	23.4; 17.2; 25; 28.1; 1.6; 4.7
Order of addition into suspension	1; 1; 2; 3; 4	1; 1; 2; 3; 4; 4	1; 1; 2; 3; 4; 4	1; 1; 2; 3; 4; 4

Another group was suspensions with combination of fillers (Table 4).

Table 4. Suspension with fly ash and combination of fillers – composition (*own research*)

Suspension	**1B**	**2B**
Component	A; B; H_2O; C; P; armature; basalt granulate	A; B; H_2O; C; P; glass fibers; basalt granulate
Composition [%]	23.1; 16.9; 26; 28; 1.5; 1.5; 3.1	23.1; 16.9; 26; 28; 1.5; 2.3; 2.3
Order of addition into suspension	1; 1; 2; 3; 4; 4; 3	1; 1; 2; 3; 4; 4; 3

The third group were suspensions with aggregates without filler (Tables 5 and 6). The aim of these suspensions was to create a material that would be enriched with the elements of today's concrete mixes. Three types of mixtures were created.

Table 5. Suspension with fly ash and aggregates, binder A + B + C – composition (*own research*)

Suspension	**1C**	**2C**	**3C**
Components	A; B; H_2O; C; P; aggregates faction 0/4	A; B; H_2O; C; P; aggregates faction 4/8	A; B; H_2O; C; P; aggregates faction 0/4 + 4/8 (2:1)
Composition [%]	14.5; 9.7; 16.1; 24.2; 1.6; 33.9	14.5; 9.7; 16.1; 24.2; 1.6; 33.9	14.5; 9.7; 16.1; 24.2; 1.6; 33.9
Order of addition into suspension	1; 1; 2; 3; 4; 3	1; 1; 2; 3; 4; 3	1; 1; 2; 3; 4; 3

During the research, a new geopolymer binder (intended primarily for suspensions with slag) was also delivered, so it was decided that this binder would also be tested for a subsuspension with fly ash and aggregate, which was the fourth group of suspensions (Table 6).

Table 6. Suspension with fly ash and aggregates, binder G – composition (*own research*)

Suspension	**1D**	**2D**	**3D**
Components	G; H_2O; C; P; aggregates faction 0/4	G; H_2O; C; P; aggregates faction 4/8	G; H_2O; C; P; aggregates faction 0/4 + 4/8 (2:1)
Composition [%]	23.1; 20; 23.1; 1.5; 32.3	23.1; 20; 23.1; 1.5; 32.3	23.1; 20; 23.1; 1.5; 32.3
Order of addition into suspension	1; 2; 3; 3; 4	1; 2; 3; 3; 4	1; 2; 3; 3; 4

1.4.2. Suspension with slag

The next phase of the research was the creation of suspension formulas that would have slag as their filler. Slag is an interesting waste product, and in connection with the geopolymer binder, a suspension may be created that can find application in vibro-pressing. Suspension for vibro-pressing consisted of 3 components as geopolymer binder, slag filler and water (Table 7). Geopolymer binders consisted of water glass, glass waste and metallurgical waste. Other modifications were optionally enriched with components that could positively affect the overall mechanical properties of the resulting material.

The designation of the fundamental individual components of the suspensions implemented was as follows:

- slag = component **F**,
- geopolymer binder (2 components in a ratio of 1.4:1) = component **G**.

Table 7 shows the composition of the trial suspension with slag.

Table 7. Composition of the trial suspension using slag (*own research*)

Component	Order of addition into suspension	Composition [%]
G	1	35
H_2O	2	27
F	3	37

In total, 9 formulations of fly ash suspensions were created. The designation of individual types of suspensions was:

- suspension with power plant slag + Plasticizer Den Braven (P) – desig. **1E**
- suspension with power plant slag + P + granular basalt – desig. **2E**
- suspension with power plant slag + P + glass fibers – desig. **3E**
- suspension with power plant slag + P + armature – desig. **4E**
- suspension with power plant slag + P + aggregate 0/4 – desig. **1F**
- suspension with power plant slag + P + aggregate 4/8 – desig. **2F**
- suspension with power plant slag + P + aggregate 0/4 + 4/8 (2:1) – desig. **3F**
- suspension with power plant slag + P + aggregate 0/4 – desig. **1G**
- suspension with power plant slag + P + aggregate 4/8 – desig. **2G**

Suspensions 1G and 2G are identical to formulas 1F and 2F, the difference is in the order of entry of the ingredients into the mixture. As part of the experiment, two main groups of suspensions were implemented, namely suspensions with one type of filler and suspensions with one type of filler and aggregate. All the suspensions realized here were intended for vibro-pressing. Table 8 shows the compositions of suspensions with slag and with one type of filler.

Table 8. Suspensions with slag and with one type of filler in suspension – composition (*own research*)

Suspension	**1E**	**2E**	**3E**	**4E**
Components	G; H_2O; F; P	G; H_2O; F; P; basalt granulate;	G; H_2O; F; P; glass fibers	G; H_2O; F; P; armature
Composition [%]	23.1; 20; 55.4; 1.5	22.4; 19.4; 53.7; 1.5; 3	22.4; 19.4; 53.7; 1.5; 3	22.4; 19.4; 53.7; 1.5; 3
Order of addition into suspension	1; 2; 3; 4	1; 2; 3; 4; 4	1; 2; 3; 4; 4	1; 2; 3; 4; 4

Table 9 shows the compositions of suspension for vibro-pressing with the presence of aggregates.

Table 9. Suspensions with slag and with aggregates (different factions) – composition (*own research*)

Suspension	**1F**	**2F**	**3F**
Components	G; H_2O; F; P; aggregates faction 0/4	G; H_2O; C; P; aggregates faction 4/8	G; H_2O; C; P; aggregates faction 0/4 + 4/8 (2:1)
Composition [%]	23; 20; 23; 1.5; 32.5	23; 20; 23; 1.5; 32.5	23; 20; 23; 1.5; 32.5
Order of addition into suspension	1; 2; 3; 4; 4	1; 2; 3; 4; 4	1; 2; 3; 4; 4

Table 10 shows the suspensions which are the same as 1F and 2F, the difference is only in the mixing procedure (order of components addition into suspension).

Table 10. Suspensions with slag and with aggregates (different factions, other order of addition) – composition (*own research*)

Suspension	**1B**	**2B**
Component	G; H_2O; F; P; aggregates faction 0/4	G; H_2O; C; P; aggregates faction 4/8
Composition [%]	23; 20; 23; 1.5; 32.5	23; 20; 23; 1.5; 32.5
Order of addition into suspension	1; 2; 3; 4; 3	1; 2; 3; 4; 3

2. Performed sample tests

In total, 21 recipes were created, which were further investigated.

Samples were cast (Fig. 2), which met the condition of cohesion and could be used for further testing (2 samples were made from each designed suspension). After solidification, none of the samples showed signs of spontaneous cracking.

Fig. 2. Part of the manufactured experimental geopolymer samples (*own research*)

The structures of the created samples were different for individual types of suspensions. The structure of suspensions with fly ash showed significantly less porosity than that with slag. This was, of course, caused by the particle size of the filler, where the fly ash used was much finer than the slag filler. It was possible to see the reinforcement used on the structure of fly ash geopolymers.

The structure of the slag geopolymers can also be used to recognize some of the reinforcements used. The structure of slag geopolymers in cross-section can be seen in Figure 3, the first sample from the left, you can see the presence of glass fibers used in the suspension and the second sample from the left you can see the use of reinforcement, i.e. steel wires. For samples with basalt (third from the left), we cannot tell at a glance whether basalt was used or not. In order to recognize the basalt particles, it would be necessary to analyze the microstructure under a microscope.

Fig. 3. Structure of slag geopolymers (*own research*)

The analysis of the structure of the created samples did not bring any new findings, the resulting structures are very porous, which corresponds to the findings of other research (Řezník, 2014).

Specimens were created for static mechanical bending and compression tests. Next, the created samples were tested. The testing of the samples was carried out on a static testing machine Inspect 250 from Hegewald & Peschke according the standard ČSN EN 1015-11 in bending and compression. A total of 42 samples with

VEPs were subjected to the test (ČSN EN 1015-11, 2020; Hela & Sokolář, 2005). The testing took place in two stages. In the first stage, bending tests were carried out on whole bars created by casting into a mold. In the second stage, the samples were cut into smaller objects suitable for a pressure test.

The bending tests involved three-point bending. A formed beam was placed between two supports, and due to the action of forces in the middle of the tested body, it broke (Fig. 4). The values of the applied force were recorded and stored for further processing.

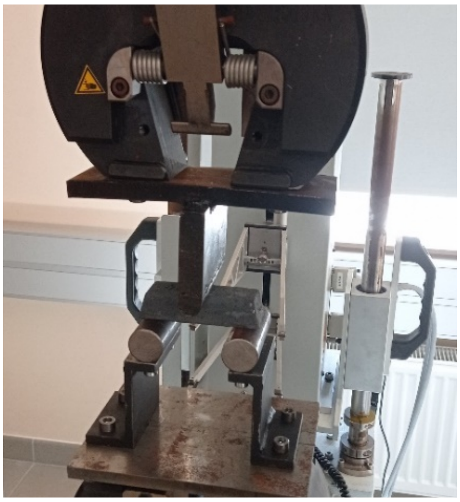

Fig. 4. Bending test (*own research*, ČSN EN 1015-11, 2020)

Subsequently, a pressure test was carried out. The implementation of the pressure test is shown in Figure 5.

Fig. 5. Pressure test (*own research*, ČSN EN 1015-11, 2020)

3. Measured values

Thanks to static tests of the material for bending and pressure, the values of the maximum force (Fmax) acting on the material before its failure were determined. These values are summarized in Table 11.

Table 11. Overview of used raw materials (*own research*)

No.	Sample	Bending test, Fmax [N]	Pressure test, Fmax [N]
Mixtures with fly ash			
1.	**1A**	12	5982
2.	**2A**	405	4043
3.	**3A**	572	4898
4.	**4A**	323	7422
5.	**1B**	220	4021
6.	**2B**	771	6204
7.	**1C**	128	1421
8.	**2C**	113	3675
9.	**3C**	140	3728
10.	**1D**	288	2102
11.	**2D**	179	1395
12.	**3D**	262	2211
Mixtures with power plant slag			
1.	**1E**	14	1999
2.	**2E**	62	659
3.	**3E**	102	1672
4.	**4E**	46	613
5.	**1F**	88	2663
6.	**2F**	60	2725
7.	**3F**	64	720
8.	**1G**	62	1653
9.	**2G**	82	1753

Figure 6 is a graph with the results of the bending test for mixtures with fly ash. It can be seen that the best fly ash geopolymer in terms of the bending test is sample 2B (suspension with the addition of glass fibers and granular basalt). Good bending strength values were also achieved by sample 3A (suspension with a separate filler, i.e. with glass fibers).

From the resulting values of the bending tests, it can be stated that in the suspensions created with the filler alone (designation 1A – 4A), there is an increase in bending strength, especially when glass fibers and basalt granulate are used. The suspension with only plasticizer achieved a very low strength value.

For samples in which two reinforcing fillers were present (designation 1B and 2B), the strength increased only with the combination of glass fibers and basalt granulate compared to suspensions with a separate filler. An interesting finding is the reduction of the strength value when the reinforcement and basalt granulate are combined compared to the suspension with a separate filler.

For suspensions with the presence of aggregates (designation 1C – 3C), the greatest measured value of bending strength was for the sample that was composed of two fractions of aggregates.

The use of a different geopolymer binder in suspensions with aggregates (1D – 3D) resulted in an almost two-fold increase in their strengths compared to samples 1C – 3C.

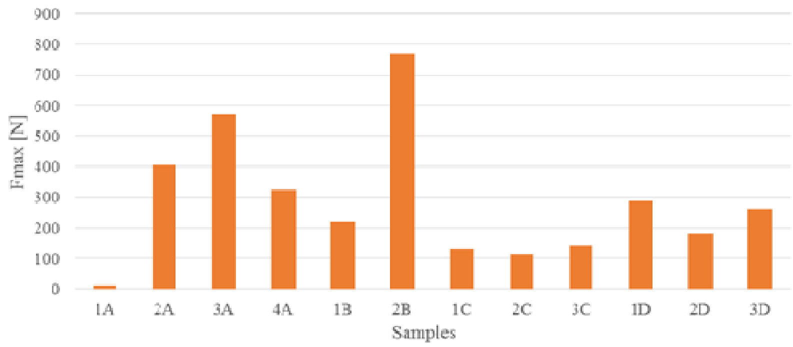

Fig. 6. Bending test results – fly ash geopolymers (*own research*)

Figure 7 shows a graph with the results of the bending test for mixtures with slag. Bending tests for geopolymers with slag reached a maximum value of 102 N for sample 3E. That is, in the case of geopolymeric suspension with glass fibers.

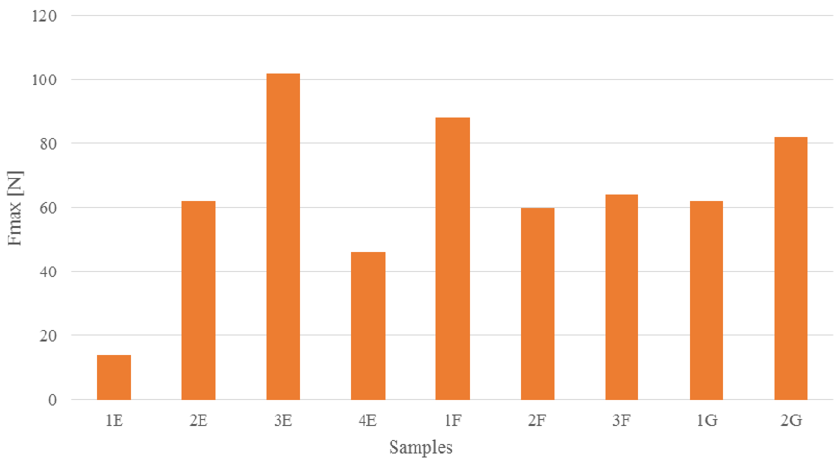

Fig. 7. Bending test results – power plant slag geopolymers (*own research*)

In the bending tests of slag geopolymers, there was an increase in the strength of the group of samples with one added filler. Again, the use of basalt granulate or glass fibers in suspension has proven successful. After the addition of basalt granulate to the suspension, there was a fourfold increase in the strength value compared to the sample with only plasticizer. In the suspension with glass fibers, this increase was even fivefold. Adding the reinforcement itself to the suspension increased the resulting strength of the sample by a factor of three.

In the group of slag geopolymers with aggregates (1F – 2G), there was an increase in strength compared to the original suspension with only a plasticizer in all samples created. The change in the mixing procedure of individual components for sample 1G and 2G did not show an effect on the overall flexural strength, as there was a decrease in strength between samples 1F and 1G and an increase in samples 2F and 2G.

Figure 8 further presents the results of the pressure test for geopolymers with fly ash.

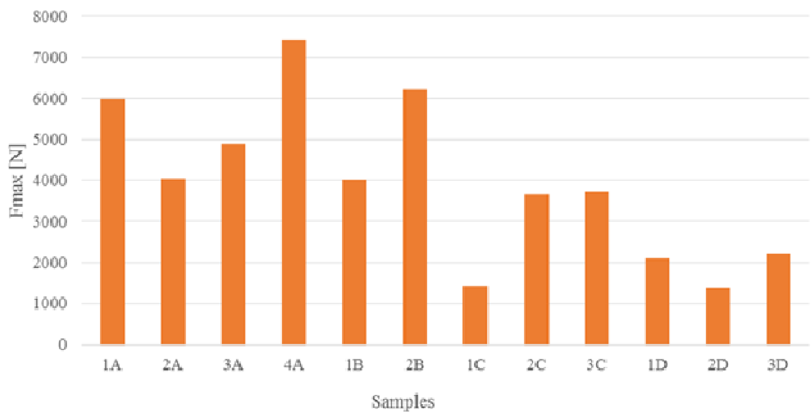

Fig. 8. Pressure test results – fly ash geopolymers (*own research*)

The highest values were achieved by sample 4A (suspension with armature). Samples 2B and 1A also achieve high values. These are geopolymer suspensions with granular basalt and glass fibers (2B) and the very primary structure of geopolymer with fly ash (1A).

From the results of pressure tests for fly ash geopolymers, it is clear that the strength values of suspensions with a separate filler are higher than for suspensions with a combination of two fillers or for suspensions with aggregate as the main filler. The only exception is sample 2B.

For suspensions with aggregates (1C – 3D), there was an increase in strength values, especially when using a combination of fractions 0/4 and 0/8. The replacement of the geopolymer binder in suspensions with aggregates did not show an increase in strength in samples 2D and 3D, on the contrary, it decreased. The only sample that showed an increase in compressive strength compared to the original version with a different type of binder was the sample 3D.

Figure 9 presents the pressure test results for geopolymers with power plant slag.

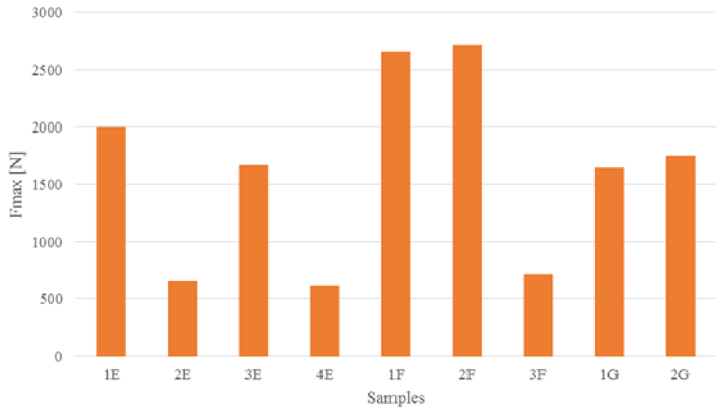

Fig. 9. Pressure test results – geopolymers with power plant slag (*own research*)

The compressive strength values of geopolymers with slag did not reach the values of the ash geopolymers. Sample 2F achieved the highest strength value in the pressure tests. It is a geopolymeric suspension with the addition of aggregate fraction 4/8. Sample 1F, which is a slurry with type 0/4 aggregate filler, is the second best sample in terms of compressive strength.

Pressure tests of suspension 1E with plasticizer achieved higher strength values than samples using a separate filler (2E – 4E).

In suspensions with aggregates, two samples (1F and 2F) experienced an increase in compressive strength compared to suspensions with a plasticizer. The mixing procedure did not have a positive effect on the resulting compressive strength, and on the contrary, reduced it (1G and 2G).

Conclusions

The research dealt with the use of secondary energy products in the preparation of possible new construction mixtures. Fly ash and power plant slag were chosen for this purpose.

In total, 21 recipes were created, which were further tested. For all these recipes, the mixture was mixed successfully and it showed no signs of discontinuity of the individual components. The obtained samples were further tested by static tensile and bending tests.

The results of the performed static tests showed that ash geopolymer suspensions showed significantly greater strength compared to suspensions with power plant slag. In some cases, this difference was several times greater in favor of fly ash suspensions.

Another interesting finding was the behavior of some reinforcing fillers when mixing the mixture itself, when, for example, glass fibers compacted the overall mixture significantly and for complete mixing it would be necessary to find another mixing device.

If we look at the results of static tests and focus on suspensions that contain reinforcing fillers, their behavior in some samples in the form of the resulting strength of the material is not regular and often actually reduces the strength of the entire mixture.

An overall view of the resulting values of both types of tests of all samples brought the finding that fly ash suspensions achieve higher compressive and bending strength values than suspensions with power plant slag.

Glass fibers were the best filler, which significantly influenced the bending strength values. They have been shown to improve the flexural properties of both fly ash and slag geopolymers.

It can also be stated that, in general, the structure of all samples obtained was very porous, which fits into the overall context of the findings so far, and high porosity applies to these materials in general, and even other combinations of input raw materials did not bring new findings in this matter.

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