Workability and Performance Testing of Alkali-Activated Luminescent Composite

Jana Boháčová[1*)], Lukáš Procházka[2)], Filip Khestl[3)], Lucie Hulvová[4)]

[1*)] Faculty of Civil Engineering, VSB- Technical University of Ostrava, L. Podeste 1875, Ostrava- Poruba, 70800, Czech Republic; jana.bohacova@vsb.cz; https://orcid.org/0000-0001-9932-1688
[2)] Faculty of Civil Engineering, VSB- Technical University of Ostrava, L. Podeste 1875, Ostrava- Poruba, 70800, Czech Republic; lukas.prochazka@vsb.cz; https://orcid.org/0000-0002-2829-5643
[3)] Faculty of Civil Engineering, VSB- Technical University of Ostrava, L. Podeste 1875, Ostrava- Poruba, 70800, Czech Republic; filip.khestl@vsb.cz; https://orcid.org/0000-0001-6260-6831
[4)] Faculty of Civil Engineering, VSB- Technical University of Ostrava, L. Podeste 1875, Ostrava- Poruba, 70800, Czech Republic; lucie.hulvova.st@vsb.cz

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Abstract

This study was focused on the development and testing of luminescent composite based on alkali-activated granulated blast furnace slag. The composite was intended for use as a secondary luminescent layer of visual safety elements in transport infrastructure applications. The evaluation included compressive and flexural strengths, adhesion to different substrates (concrete and asphalt), slip resistance, bulk density, and fresh mortar consistency. The results show that the compressive and flexural strengths, as well as slip resistance, are sufficient for intended application. Experiments also revealed unexpectedly long initial and final setting times and relatively low adhesion values, which may pose challenges for the proposed use. Further research in terms of durability is needed. For use in traffic engineering, future testing should include frost resistance and resistance to de-icing agents.

Keywords: *Luminescence, Alkali-activated, Blast Furnace Slag, Composite, Transport Infrastructure*

1. Introduction

Luminescence is a physical phenomenon in which certain substances – so-called luminophores – emit light. This process begins with the excitation of electrons to a higher energy level. They then return to their ground state without increasing the temperature of the substance. Depending on the duration of the afterglow, we distinguish between fluorescence, where the light effect disappears almost immediately, and phosphorescence, where the luminescence can persist for several seconds to hours [1, 2].

Coloured pigments have been used in construction for many years, while the application of luminescent pigments is a relative novelty. Currently, these pigments are used in the form of coatings, very often very thin layers of material, but the lifespan of the surface created in this way is relatively short. It would be ideal to create products entirely from a material with a luminescent pigment, but this is prevented by its high price.

Therefore, the aim of this experiment is to design mixtures with luminescent pigment based on alkali-activated blast furnace slag and to verify whether it is possible to add these "luminous" layers to selected surfaces of structures additionally, i.e. whether the cohesion with the primary material will be sufficient, etc. As a result, the layer formed on the surface will be thicker than paints and therefore have greater resistance to mechanical damage and thus a longer service life.

This experiment develops previous research work focused on the possibilities of preparing luminescent mixtures and further deepens them. This is mainly realized by optimizing the alkali-activated mixture for the intended use and verifying adhesion to the base layer. In previous work, Portland cement, white cement and also alkali-activated blast furnace slag with filler replacement in the amount of 5%, 10% and 15% by weight were tested [3]. The results showed that pigment is not applicable in Portland cement due to the gray color of the cement. There was not much difference between the mass with white cement and blast furnace slag, but due to the price, blast furnace slag was recommended as the basis for further development. As for the pigment content, due to the resulting effect and its high price, 10% pigment per weight of the binder was chosen as the optimal amount [3].

The aim of the experiment was to create an alkali-activated material with luminescent properties that would meet the required properties (adhesion to the substrate, strength, processability, slip resistance). Finely ground granulated blast furnace slag was used as a binder. The filler was quartz sand of the PG1 fraction, and anhydrous sodium metasilicate in powder form was used as an alkaline activator. The selected photoluminescent pigment is characterized by its light green color and long-lasting luminous effect for up to 12 hours.

2. Luminiscence in construction and alkali-activated materials

Luminescence is defined as the process by which atoms or molecules absorb energy, enter an excited state and then release this energy as the light. Substances responsible for this phenomenon are called luminophores. This phenomenon usually produces visible, ultraviolet, or infrared radiation [4].

Main types of luminescence by excitation method include:

Photoluminescence – excitation by light

Fluorescence – fast process, light disappears immediately when the source is removed.

Phosphorescence – slower, light persists after the source is turned off.

Chemiluminescence – excitation by chemical reaction

Bioluminescence – a special case in living organisms (e.g., fireflies, marine organisms).

Electroluminescence – excitation by electric field or current (e.g., LEDs).

Cathodoluminescence – excitation by electron beams (CRT screens, oscilloscopes).

X-ray luminescence – excitation by X-rays.

Radioluminescence – excitation by radioactive radiation (e.g., old watch dials painted with radium).

Triboluminescence – excitation by mechanical action (friction, breaking crystals).

Sonoluminescence – excitation by sound waves (ultrasound in water creating light flashes).

Thermoluminescence – emission of light upon heating a substance previously exposed to radiation.

Cryoluminescence – emission of light upon cooling certain materials to very low temperatures [4, 5].

Luminescence is in construction used primarily on the field of safety and aesthetics. It is mainly used in the production of emergency signs and escape routes. It ensures visibility even in the event of a power outage. It is also very often used in transport infrastructure as luminescent coatings on roads, sidewalks or crossings, it helps to increase traffic safety at night. In architecture and interior design, luminescent pigments are mainly used for decorative purposes, for example on facades or floors, thus enhancing the originality of buildings. Saving energy is also important aspect, as photoluminescent materials can partially replace artificial lighting.

Alkali-activated systems, thanks to the use of suitable raw materials and favorable final properties, are among the most important candidates for replacing Portland cement. They are based on the alkaline activation of latent hydraulic substances or pozzolans, which is their main advantage, since they reduce the carbon footprint by using secondary raw materials, which is important primarily from the point of view of sustainable development [6].

In previous experiments, it was found that the use of pigment significantly reduces the strength of the prepared materials, which is an undesirable effect. The essence of this experiment is therefore to verify whether there is indeed a degradation of the strength characteristics as indicated by previous studies, and at the same time to assess how this phenomenon is reflected in other key properties that determine the real use of these materials in construction. The aim is therefore not only to confirm or refute the existing knowledge, but also to verify other parameters important for real use in practice [3].

3. Materials and methods

In the experiment, finely ground granulated blast furnace slag (specific surface according to Blain 400m^2/kg, SiO_2 34%, Al_2O_3 12%, FeO 1%, MnO 1.4%, CaO 42%, MgO 9%, P_2O_5 0.05%, CaS 1.3%), sodium metasilicate (silicate modulus of 1.0), quartz sand (PG1 fraction due to EN 196-1 standard. The sand is rinsed, dried and sieved to keep the dust content as low as possible, with high mechanical and chemical resistance. Humidity max 0.2%. Minimum SiO_2 content is 99%.), powder luminophore PLE-P-Z-4B green color (granularity 65-85µm and luminosity 640 mcd/m² in the first 10 minutes and then luminosity 105 mcd/m² for at least 60 minutes), and mixing water.

Due to the use of only the PG1 fraction of quartz sand, instead of all three standard fractions compared to previous experiments, the specific surface area of the aggregate increased and a greater amount of water was required. The aim of this experiment was to find the ideal ratio between the binder component and the filler to obtain maximum adhesion to the substrate, with regard to the strength and workability of the mixture. In the first phase, the basis was the previous work, where a mixture with the following composition was used: 14.65 g of blast furnace slag, 3.58 g of water, 43.95 g of quartz sand, 1.46 g of luminescent pigment, 4.11 ml of water glass. The previous mixture was modified and the water glass was replaced with anhydrous granulated sodium metasilicate [3].

In search of a suitable optimum, the mixtures were applied to three pre-formed molds measuring 5x5 cm and with different heights of 2, 4, and 6 mm. Many different mixtures were tested, all initially without pigment, until a mixture that was satisfactory in all respects (workability, applicability, adhesion to the base layer, strength) was created.

Figure 1 shows the appearance of several tested mixtures with composition in Table 1. It is clear that although the differences in composition were minimal, the visual differences between the mixtures were significant. Mixture marked 1 was the best visually, but it did not adhere to the base laye at all. Mixture 2 adhered, but contained too much water, and therefore did not hold the desired shape - it flowed after demoulding. Mixture number 3 was discarded due to poor application, which is also evident in the picture, as the surface was tearing during application. Mixture 5 was so dry that it did not hold its shape after demoulding. Mixture marked 4 met all the requirements and was chosen as the optimal mixture.

Tab. 1. Composition of selected tested mixtures

Mixture	Slag [g]	Sand [g]	Water [g]	Activator [g]
1	20.6	61.6	10	4.6
2	20.6	61.6	15	4.6
3	20.6	51.6	10	4.6
4	30.0	60.0	15	4.6
5	30.0	60.0	10	4.6

Mixture 4 seemed to be optimal in all selected parameters – it was not too wet, it applied well, it adhered very well to the concrete tile and it seemed solid. It was mixed again the next day in the same composition and also with a new luminescent pigment, for comparison of properties. The pigment slightly affected the consistency of the material, which did not reduce its ability to be applied, but rather positively affected its cohesion (it did not fall apart), as can be seen in the Figure 2 (on the left side without pigment; on the right side the mix with pigment).

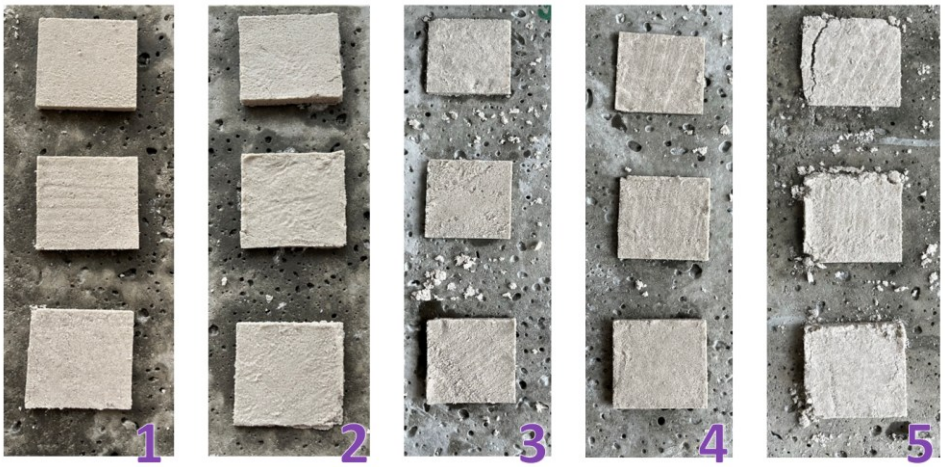

Fig. 1 Visual differences between the mixtures and different layers (bottom 2mm, middle 4mm, top 6mm thick layer)

Fig. 2 Visual differences between the mixtures - on the left side without pigment; on the right side with pigment (bottom 2mm, middle 4mm, top 6mm thick layer)

This mixture was selected for further experiments. The properties of the fresh mixture were determined, namely the consistency, the bulk density and setting times. For the hardened mixture, the bulk density, the flexural strength, the compressive strength, the luminescence of the bodies, the adhesion to the base layer, and the resistance to slip was verified.

The individual components were weighed using a digital scale with an accuracy of ± 1g. Automatic laboratory mixer Beton System MI-CM5A was used to prepare the mixtures according to the EN 196-1 standard. Properties of the fresh mixture and the mechanical properties after the prescribed curing period (7 and 28 days) were tested. For testing of hardened mixture properties, standard material samples of 40x40x160mm were prepared. During the curing time, all test specimens were stored in the environment with relative humidity of 98% and temperature of 31°C. Properties of fresh mixture were then tested according to EN 1015-3: Methods of test for mortar for masonry – Part 3: Determination of consistency of fresh mortar (by flow table), the bulk density was tested according to EN 1015-6: Methods of test for mortar for masonry – Part 6: Determination of bulk density of fresh mortar. The setting times and soundness were determined in accordance with EN 196-3: Methods of testing cement – Part 3: Determination of setting times and soundness [7, 8, 9, 10].

Properties of hardened mixtures were tested according to EN 1015-10: Methods of test for mortar for masonry – Part 10: Determination of dry bulk density of hardened mortar. Strengths were determined according to EN 1015-11: Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar [11, 12].

Important parameter for intended use of tested mixture is adhesion, which was determined in accordance with EN 1015-12. The test involves measuring the force required to detach a surface treatment of a specified area from the substrate by a perpendicular pulling force. Before determining the adhesion, test samples need to be prepared. This was achieved by applying a tested luminescent composite in three different thicknesses (2, 4, and 6 mm) to pre-prepared concrete and asphalt tiles. To prepare the samples, square molds of the required heights (2, 4, and 6 mm) and dimensions (30x30 cm) were first treated with release oil. These molds were then placed on the damp surface, and the composite substance was manually applied using a spatula. The molds were removed immediately after application. The prepared samples were subsequently covered with foil and stored in a laboratory environment for the duration of the maturation period.Adhesion to substrate was tested according to EN 1015-12: Methods of test for mortar for masonry – Part 12: Determination of adhesive strength of hardened rendering and plastering mortars on substrates [13].

When determining adhesion, the surface is first cleaned, and the test disc is attached using epoxy adhesive. The test disc must always be centered and fully adhered. Then, the surface layer is cut using a drill with a core drill bit (Fig. 12). The actual detachment of the disc occurs at a defined, constant rate of stress increase, and the highest tensile force value is recorded at the moment of detachment.

Slip resistance was determined according to EN 14231: Determination of slip resistance by means of the pendulum tester. This test is

used to evaluate anti-slip properties of material. It is important for assessing flooring materials intended for areas with pedestrian traffic, especially for outdoor conditions. The test helps ensure user safety by measuring the potential risk of slipping. Results from this test are crucial for selecting suitable materials for use in walking surfaces and flooring applications [14].

4. Results and discussion

Final properties are given in Table 2.

Tab. 2. Properties of selected mixture

Parameter	Result
Consistency [mm]	114
Initial setting time [min]	420
Final setting time [min]	495
Bulk density fresh mixture [kg/m^3]	2150
Bulk density hardened miture [kg/m^3]	2110
Flexural strength 7 days [MPa]	2.7
Flexural strength 28 days [MPa]	5.1
Compressive strength 7 days [MPa]	18.6
Compressive strength 28 days [MPa]	56.2

The results show that the flexural and compressive strengths are sufficient for the intended application. However, the results obtained for the setting time are somewhat unexpected. The initial setting time was determined to be 420 minutes (7 hours), and the final setting time was recorded at 495 minutes (8 hours and 15 minutes). These values are relatively high. This extended setting time may be attributed to several factors, such as the age and partial hydration of the blast furnace slag, as well as it could be influenced by the presence of pigment. This observation is consistent with findings from other studies, such as [15] where reported that using weaker alkaline activators in slag-based systems can significantly prolong the setting time and delay early strength development.

The results of adhesion to the substrate are presented in the following Table 3 and example of testing is visible in Fig. 3.

Adhesion values for the 2 mm and 6 mm thicknesses were identical on concrete substrate, both reaching 0.6 MPa. On the contrary, 4 mm thickness showed a lower adhesion value of 0.4 MPa. On the asphalt substrate, the adhesion values increased progressively with layer thickness: 0.2 MPa for the 2 mm layer, 0.3 MPa for the 4 mm layer, and 0.4 MPa for the 6 mm layer.

Determined adhesion values are relatively low in comparison to commonly accepted standards for reliable bonding. While adhesion to concrete showed results at certain thicknesses (up to 0.6 MPa), and the values on asphalt ranged only between 0.2–0.4 MPa. These levels may not be sufficient for long-term durability under mechanical or environmental stress. It is recommended to further investigate surface treatment methods, such as the use of an appropriate adhesion primer or bonding bridge, to enhance interfacial strength.

Tab. 3. Adhesion to the substrate, Slip resistance

Parameter	Result
Adhesion to concrete [MPa]	0.5
Adhesion to asphalt [MPa]	0.3
SRV dry conditions [-]	83
SRV wet conditions [-]	70

Fig. 3. Adhesion to the substrate testing

The slip resistance was tested in accordance with EN 14231 using the pendulum method. Measurements were conducted under both dry and wet conditions. Slip Resistance Value (SRV) reached 83 in dry conditions and value of 70 in wet conditions. These results indicate sufficient and safe slip resistance even under wet conditions, which makes this material suitable for use on walking surfaces where slip prevention is important.

5. Conclusion

The aim of the experiment was development of a luminescent composite based on alkali-activated granulated blast furnace slag and verification of its properties for potential use as a secondary luminescent layer, for example in transport infrastructure.

The investigated properties included primarily compressive and flexural strength, adhesion to underlying materials, and additional characteristics such as the consistency of the fresh mixture and bulk density.

Compressive and flexural strengths were tested after 7 and 28 days. The average compressive strength at 7 days reached 18.6 MPa, increasing to 56.2 MPa after 28 days. The flexural strength average was 2.7 MPa after 7 days and 5.1 MPa after 28 days. In contrast to compressive strength, no significant further increase in flexural strength was observed between the two testing periods.

Adhesion was assessed on two different substrates: concrete and asphalt. The composite was applied in three-layer thicknesses – 2 mm, 4 mm, and 6 mm. The results showed that adhesion was influenced more by the applied layer thickness and application quality than by curing time. Better adhesion was achieved with thicker layers, especially on the concrete, where values reached up to 0.6 MPa. On asphalt, adhesion values were lower, ranging from 0.2 to 0.4 MPa, this may limit the durability of the layer without further surface treatment. These results align with conclusions, where was showed that the interfacial transition zone between alkali-activated binders and substrates plays a crucial role in overall performance.

Slip resistance was measured under both dry and wet conditions. The Slip Resistance Value (SRV) reached an average of 83 in dry conditions and 70 in wet conditions. These results indicate sufficient slip resistance for use in walkable surfaces, under both dry and wet environments.

In conclusion, the developed composite showed promising results for potential practical use, however, further development and testing is needed. For applications in traffic engineering such as into safety elements, it will be necessary to evaluate the material's resistance to frost and de-icing chemicals.

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