sciendo

Civil and Environmental Engineering
Vol. 20, Issue 1, 307-318, DOI: 10.2478/cee-2024-0024

PROPERTIES OF SELECTED ALKALI-ACTIVATED MATERIALS FOR SUSTAINABLE DEVELOPMENT

Jiri NEMEC[1], Radoslav GANDEL[1], Jan JERABEK[1,*], Oldrich SUCHARDA[1], Vlastimil BILEK[1]

[1] Faculty of Civil Engineering, Department of Building Materials and Diagnostics of Structures, VSB - Technical University of Ostrava, Ludvíka Podéště 1875/17, 708 00 Ostrava-Poruba, Czech Republic.
[*] corresponding author: jan.jerabek@vsb.cz

Abstract

Concrete, which is based on the use of Portland cement as a binder, is often used as a structural material in the construction industry. However, the production of cement has a high energy demand. Alkaline-activated systems, for example, have the potential to replace cement with suitable substitutes, and this also puts the raw materials created as by-products from industrial processes to the fore. The presented research focuses on three selected variants, where the goal is to compare key properties from the point of view of material engineering and structural design. Tests of the mechanical properties of the examined materials are carried out and their durability is compared, namely frost resistance, resistance to chemical and de-icing substances and resistance to elevated temperature. As part of the main design criterion of structure, the resulting average compressive strengths of the selected alkali-activated materials ranged from 52.8 to 62.8 MPa.

Keywords:

Alkaline activated material;
Geopolymer;
Cementless concrete;
Mechanical properties;
Durability.

1 Introduction

In the building industry, concrete, which is based on the use of Portland cement as a binder, is often used as a construction material [1], for example as HPC concrete for bridges and beams [2]. However, cement production is highly energy intensive and accounts for up to about 7% of total CO_2 emissions in the world [3]. The need for innovation of concrete recipes and the careful use of raw materials was also stated within the framework of the sustainability principles of designing concrete structures according to the forthcoming Model Code 2020 recommendation from the global fib organization for concrete [4]. The potential to replace cement with suitable substitutes [5], e.g., alkaline-activated systems, as stated by prof. Palomo [6] focuses on raw materials created as by-products from industrial processes. Typically, these are blast-furnace slag and power plant fly ash [7], which with suitable additives and admixtures, thanks to favourable hydraulic properties, can partially or completely replace the cement binder in concrete [8]. The topicality of the need to use secondary raw materials as part of the partial replacement of Portland cements can also be demonstrated by the development of low-carbon cements, where cements of the CEM I category according to ČSN EN 206 [9] will gradually be limited in production [10]. Possible solutions include the use of hybrid cements [11]. Research and testing of alkaline activated materials [12, 13, 14] has been going on for several decades, but its use in practice is still at an early stage. Frequent limitations of experimental programs include that they focus only on one selected property or description, and the characterization of the materials used is insufficient for wider generalization [15, 16]. From the point of view of mechanical properties, it is possible, for example, by suitable optimization of the recipe for the same raw materials to achieve better compressive properties than for concrete with Portland cement, when compressive strength is typically required for structural use. However, problematic aspects include the production technology itself, shrinkage, creep, durability and resistance. With the use of new concrete formulas, new microstructural bonds and elemental composition are also created, which are suitable to be studied using optical and electron microscopy [17]. Among the essential knowledge so far is that the composition of alkali-activated materials, compared to typical concrete, is not easily transferable [18] to the Czech Republic due to local differences. It is therefore necessary to look for solutions in the local conditions of raw material sources while respecting efficiency, economy and environmental effects. Based on the above information, an

© Author(s) 2024. This work is distributed under the Creative Commons BY 4.0 license (https://creativecommons.org/licenses/by/4.0/).

experimental program based on the use of domestic and secondary raw materials is designed, which focuses not only on mechanical properties, but also on a number of other specialized tests of materials alternative to conventional concrete and its "lightweight" variant. A detailed description of the properties will increase the potential for application use. Specialized tests will focus on resistance to chemical and de-icing substances, frost resistance, or tests of mechanical properties with regard to exposure of concrete to elevated temperatures. The expected output should be a balance of strength-mechanical and durability properties of alkali-activated materials containing local secondary raw materials and optimization of the combination of input raw materials. The mentioned program is part of a larger research experiment.

2 Experimental program and recipes

The aim of the presented experimental program was to determine the mechanical and durability properties of three different mixtures of alkali-activated concrete, then to evaluate these properties and compare the differences between the properties of these three materials (recipes) [19]. The recipes are shown in Table 1. The first alkali-activated material (AAM) recipe is the basis for two other recipes, which are only modified. Alkali-activated material with power plant fly ash (AAM+P) is modified with Detmarovice Fly ash with specific surface 340 m^2/kg, which was added instead of 30% of JMŠ 420 Slag with 420 m^2/kg specific surface area. For alkali-activated material with Liapor (AAM+L), part of the fine aggregate was replaced with lightweight aggregate Liapor 1/4, 500 in the amount of 81 kg per 1 m^3 of the mixture.

Table 1: Concrete recipes.

Component	Alkaline activated material	Alkaline activated material + fly ash	Alkaline activated material + lightweight aggregate (Liapor)
	(AAM)	**(AMM+P)**	**(AAM+L)**
	m [kg]	**m [kg]**	**m [kg]**
	1 m^3	**1 m^3**	**1 m^3**
JMŠ 420 blast-furnace slag	450	315	450
Fly ash of Detmarovice	-	135	-
Aggregate Liapor 1/4, 500	-	-	81
Na-water glass, M_s = 2.0	56.3	56.3	56.3
50% KOH solution	42	42	42
Mixture water	172	172	150
Chrysoplast 760	9	9	9
Aggregate 0/4 Tovacov	920	920	710
Aggregate 4/8 Litice	670	670	670
Water for soaking Liapor	-	-	22
Total mixture water	-	-	172

3 Properties of hardened alkali-activated concrete

All strength characteristics were tested on laboratory hydraulic presses FORM+TEST MEGA 100-300-10DM1 due to standards: *ČSN EN 12390-3. Testing hardened concrete – Part 3: Compressive strength of test specimens [20], ČSN EN 12390-5. Testing hardened concrete – Part 5: Flexural strength of test specimens [21]* and *testing hardened concrete - Part 6: Tensile splitting strength of test specimens [22]*. The compressive strength was tested on 40 x 40 x 160 mm beams aged 28 days. The compressive strength tests on the beams are illustrated in Fig. 1 and Fig. 2. All samples were prepared in laboratory conditions at temperatures of 21 ± 1 ℃ and humidity of 55 ± 5 % RH in an automatic mixer. then they were compacted on the selection table for about 5 seconds. Finally, they were wrapped in protective foil for 2 days, when they reached minimum handling strength. After de-molding, they were stored in a water bath with a temperature of 21 ± 1 ℃, where they ripened to the standard age of 28 days.



Fig. 1: Illustrative photo – compression test.



Fig. 2: Sample after compression test.

The resulting compressive strengths were from 52.8 to 62.8 MPa. For the AAM+P and AAM+L variants, the resulting strengths are very similar as can be seen in Fig. 3. The highest strength was achieved by the reference mixture AAM with a value of 62.8 MPa.

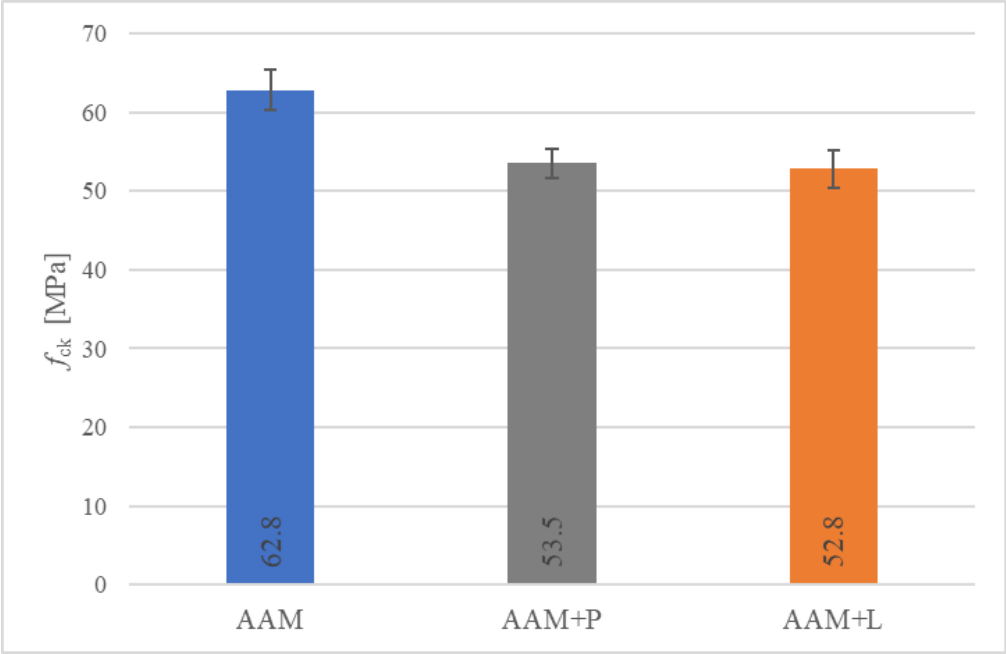


Fig. 3: Comparison of 28-day compressive strengths.

The flexural strength was also tested on 28-day-old beams. The highest strength of 4.9 MPa was achieved by the AAM reference mixture variant as can be seen in Fig. 4.

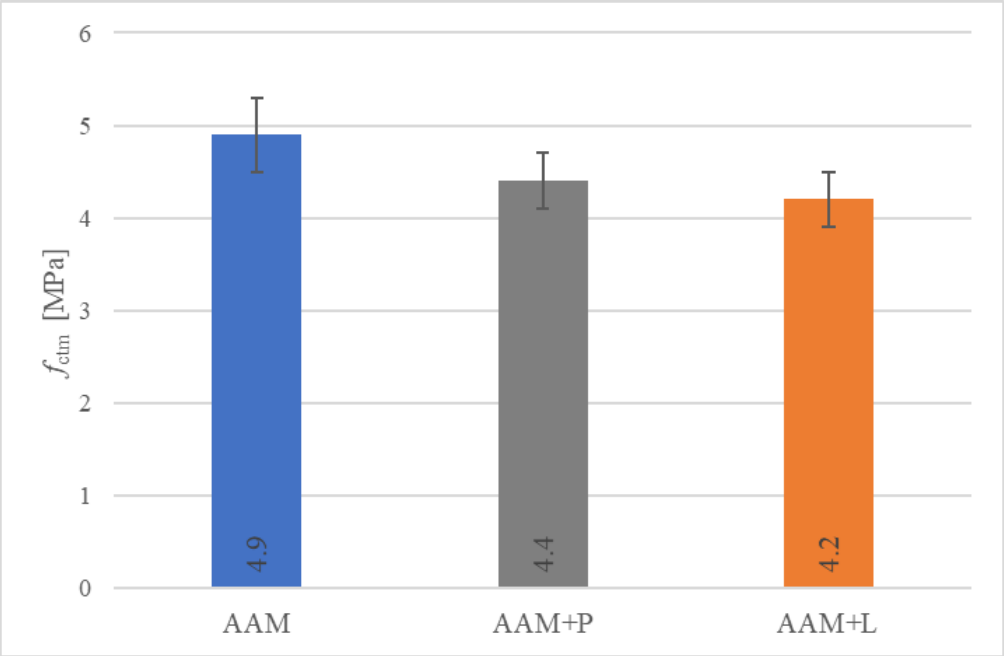


Fig. 4: Comparison of 28-day flexural strengths.

The use of fly ash or lightweight aggregate (Liapor) had a slightly negative impact on the resulting strength. The flexural strength dropped to 4.4 MPa for the variant with fly ash (AAM+P) or 4.2 MPa for the variant with lightweight aggregate (AAM+L). Another test carried out included the determination of the split tensile strength of hardened concrete. The split tensile strength (show Fig. 5 and Fig. 6) was tested on cubes with an edge length of 150 mm and an age of 28 days.

It can be seen from Fig. 7 that the reference alkali-activated material (AAM) achieved the best split tensile strength/compressive strength ratio of all three mixtures – 6.57 %. The values of the alkali-activated composite with fly ash reached approximately the same values of 5.58 % to 5.54 % as the mixture with lightweight aggregate (Liapor).



Fig. 5: The cube with an edge of 150 mm prepared for the split tensile strength test.



Fig. 6: The cube with an edge of 150 mm after the split strength test.

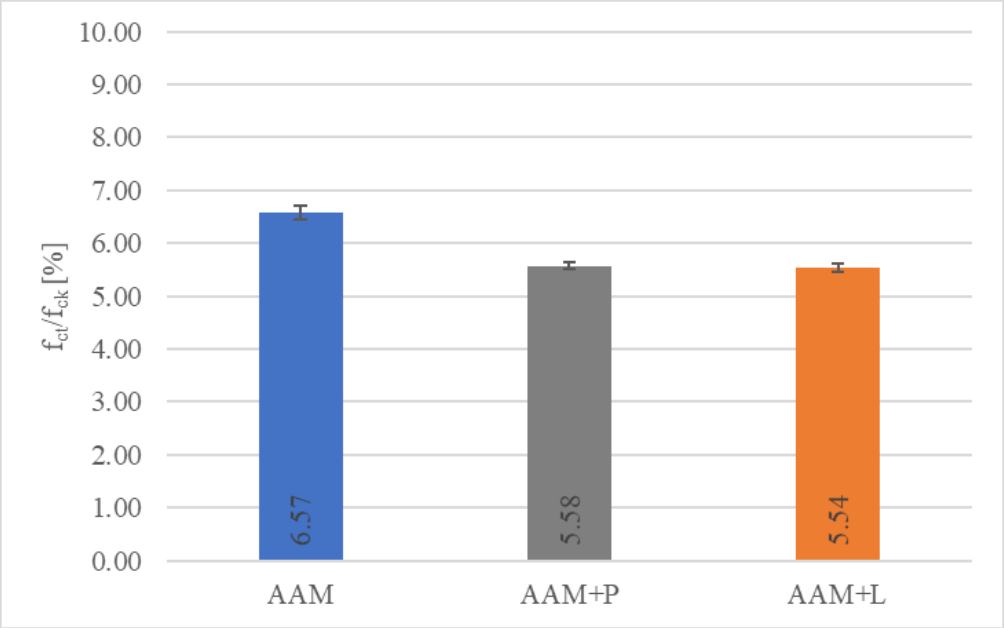


Fig. 7: Comparison of 28-day ratio of split tensile and compressive strengths.

The dynamic modulus of elasticity (Fig. 8) was tested on beams from each recipe aged 28 days by an ultrasonic pulse velocity tester-Pundit 200 device, according to standard *ČSN 73 1371. Non-destructive testing of concrete – Method of ultrasonic pulse testing of concrete. [23]* The highest average dynamic modulus of elasticity after 28 days has AAM (32.5 GPa) and the lowest AAM+P (27.4 GPa).

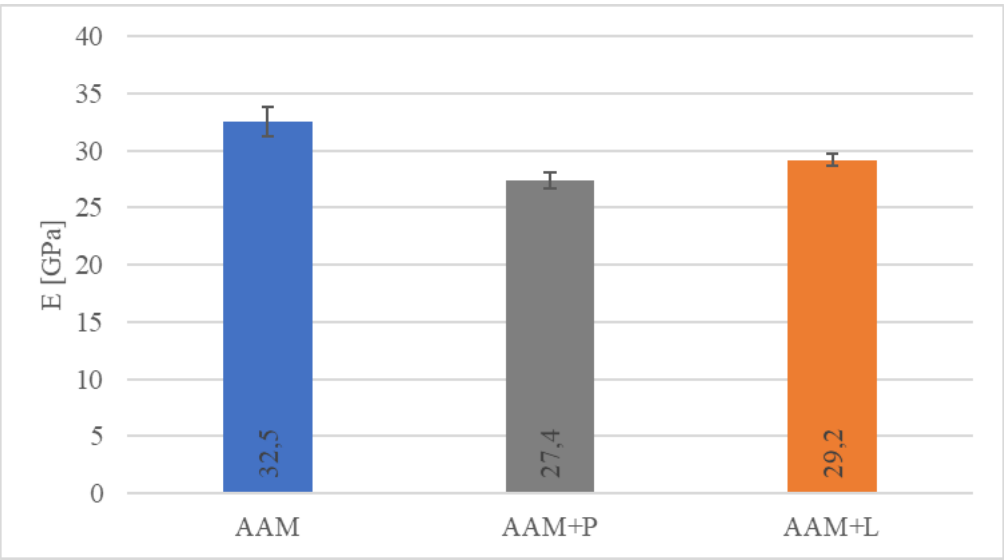


Fig. 8: Comparison of 28-day dynamic modulus of elasticity.

2.1 Effects of increased temperature on the properties of hardened alkaline concrete

The effect of increased temperature on the properties of hardened alkaline concrete was tested again on beams 28 days old and dimensions 40 x 40 x 160 mm. Before the mentioned test, the samples were dried in a dryer at 105°C for 24 hours. A reference maximum temperature of 500°C was chosen for the test, which was maintained for 2 hours, with a temperature increase of 250°C per hour in the LAC chamber furnace K120/12. Samples were stored next to each other with 1–2 centimetre gap between each one, as can be seen in Fig. 9. After this time the samples were allowed to cool in air for about 4 hours and then the samples were reweighed, and their density was calculated again.



Fig. 9: Sample placement in the furnace.

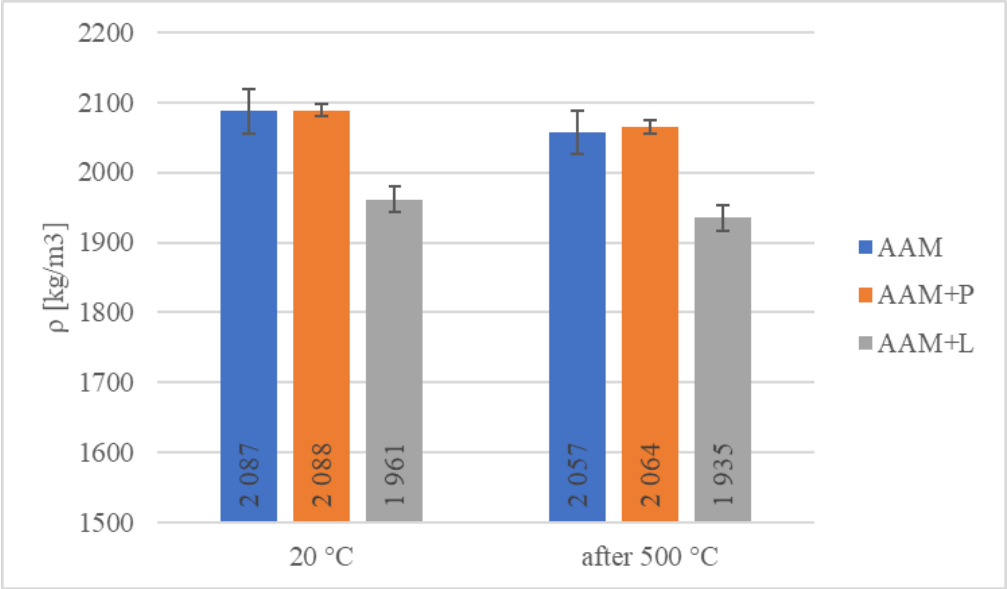


Fig. 10: Density before and after the exposure to 500 °C.

The determination of the penetration of the ultrasonic pulse before and after the exposure was also the part of the test. The samples were tested for compressive strength and flexural strength. The density was also determined, which is evaluated in Fig. 10. The resulting volumetric weight was affected by temperature at least for all three recipe variants. It can be seen from Fig. 11 that there was a significant decrease in the penetration speed of the ultrasonic pulse for all recipe variants. The decrease was typically around 40-50 %, which indicates a disruption of the microstructure of the test samples and the formation of microcracks. This was confirmed in the evaluation of compressive strength and flexural strength, which is shown in Fig. 12 and Fig. 13.

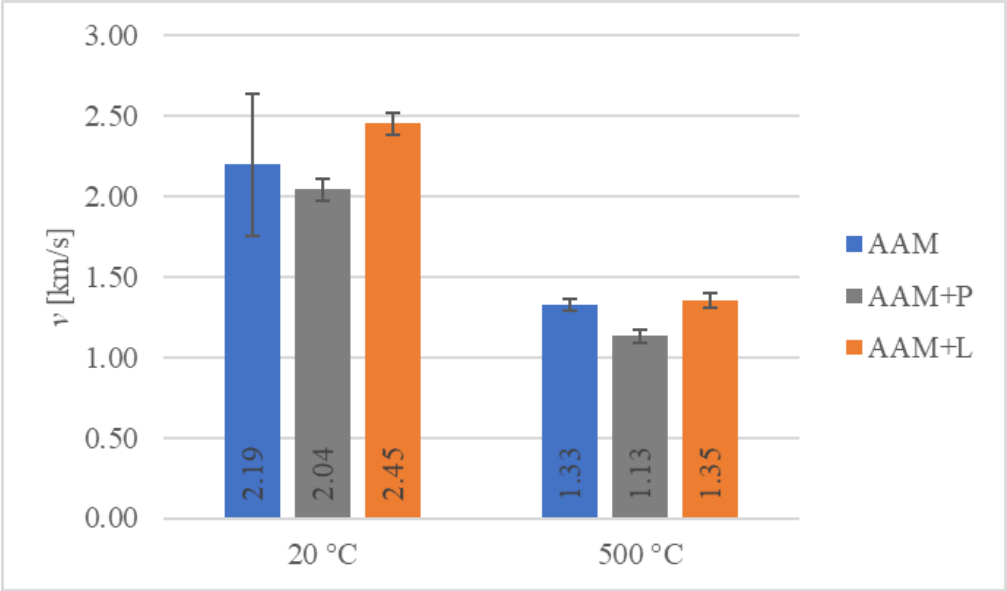


Fig. 11: Speed of passage of the ultrasonic pulse before and after the exposure to 500 °C.

It can be seen in Fig. 12 that before exposure to 500°C, AAM has the highest flexural strength (4.9 MPa) and the lowest strength has AAM+L (4.2 MPa). In contrast, after exposure to 500°C, AAM+L has the highest flexural strength (2.0 MPa) and AAM has the lowest strength (1.8 MPa). The biggest difference in strength before and after exposure was therefore for AAM (3.1 MPa) and the smallest difference was for AAM+L (2.2 MPa).

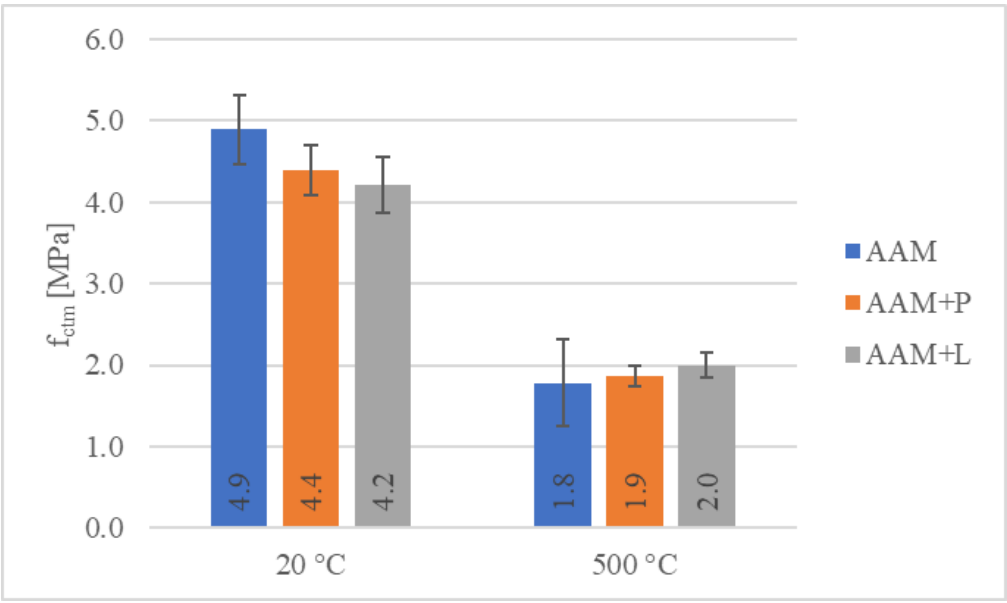


Fig. 12: Comparison of 28-day flexural strengths before and after the exposure to 500 °C.

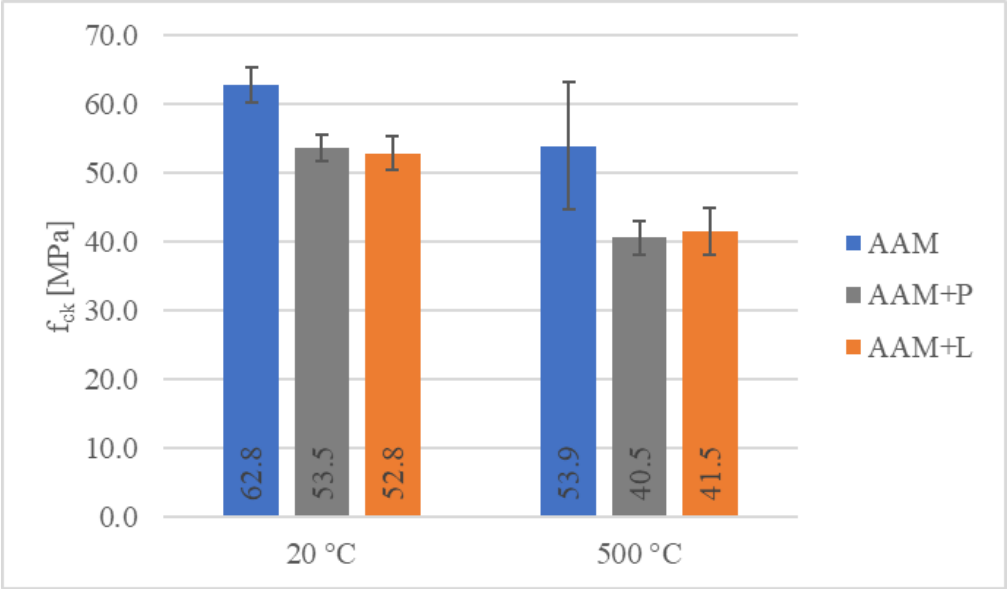


Fig. 13: Comparison of 28-day compressive strengths before and after the exposure to 500 °C.

Fig. 13 shows that AAM has the highest compressive strength both before (62.8 MPa) and after exposure (53.9 MPa). The lowest drop in compressive strength (8.9 MPa) was recorded for this recipe. The highest decrease in strength was recorded for the formula (AAM+P) with fly ash (13 MPa), which after firing had the lowest compressive strength of all mixtures (40.5 MPa).

3.2 Frost resistance

The experimental program was focused on frost resistance according to standard *ČSN 73 1322 Determination of frost resistance of concrete [24]*, where 50 cycles were chosen, taking into account the available laboratory capacities and the selected recipes. Ultrasonic wave propagation measurements were again performed before and after the freezing cycles. The tests were performed on samples 40 x 40 x 160 mm.

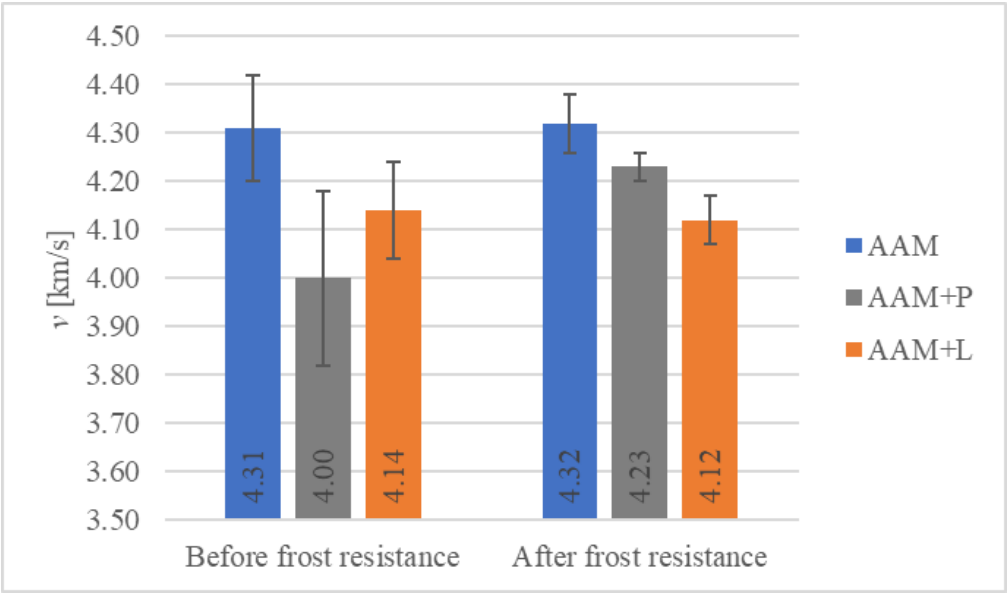


Fig. 14: Comparison of ultrasound pulse transmission speeds before and after frost resistance test.

In Fig. 14 can be seen that the frost resistance test has only a minimal effect on the transmission speed of the ultrasonic pulse AAM and AAM+L. The difference in the effect on the two materials is that in AAM the velocity increased (by 0.01 km/s) and in AAM+L it decreased (by 0.02 km/s). Frost resistance test had a more pronounced effect on the penetration speed of AAM+P (increase by 0.23 km/s).

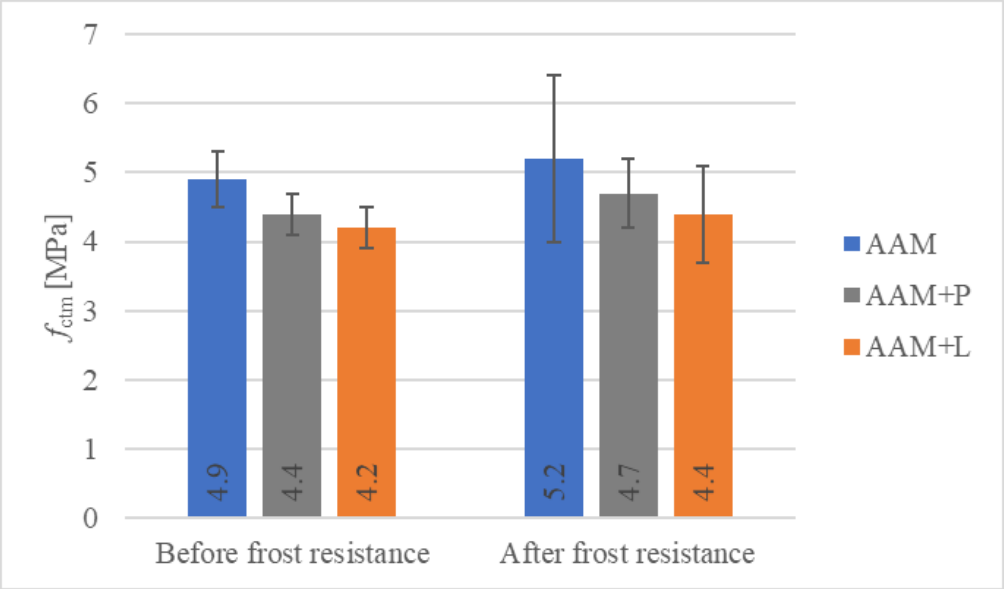


Fig: 15: Comparison of flexural strength before and after frost resistance test.

Fig. 15 shows that after the frost resistance test, the strengths of all materials increased. The greatest difference in strength before and after frost resistance was therefore created by AAM and AAM+P (0.3 MPa), and the smallest difference was created by AAM+L (0.2 MPa).

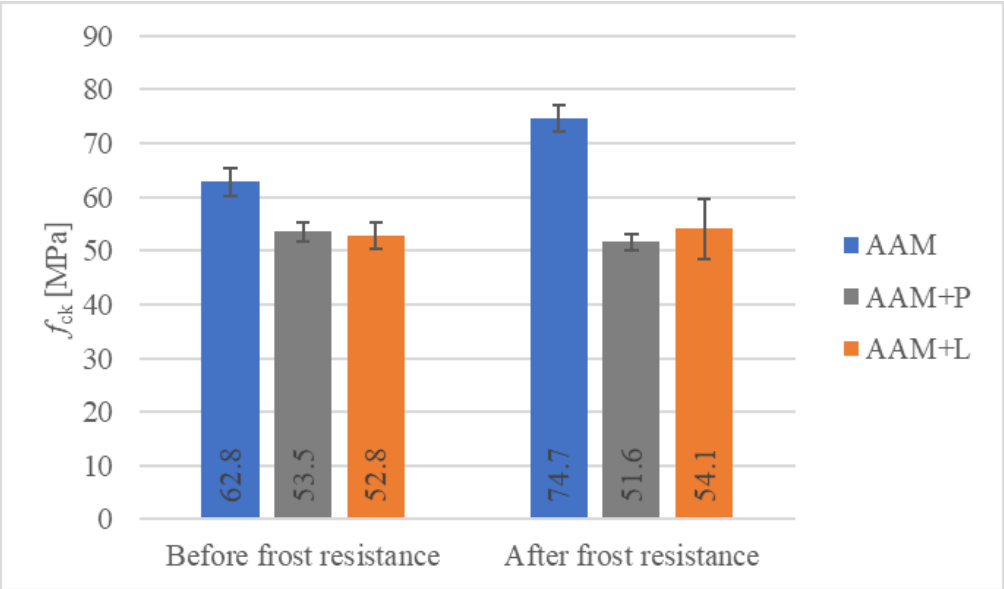


Fig 16: Comparison of compressive strength before and after frost resistance test.

It can be seen in Fig. 16 that the smallest difference in compressive strength occurred with AAM+L (an increase of 1.3 MPa) and the largest with the AAM formulation (an increase of 11.9 MPa). For AAM+P, the strength decreased by 1.9 MPa. Furthermore, an evaluation of the frost resistance coefficients was carried out, which is carried out in Table 2.

Table 2: Comparison of frost resistance test coefficients.

Coefficient of frost resistance	AAM	AAM+P	AAM+L
For flexural strength [%]	106	107	105
For compressive strength [%]	119	96	102

From Table 2, it can be clearly determined that the frost resistance test had a negative impact only on the compressive strength of AAM+P. For the other materials, the flexural and compressive strength increased after this test. For a better evaluation of the frost resistance of these materials, it is necessary to leave the samples in the freezing device for a greater number of cycles than 50.

3.3 Resistance to water and defrosting chemicals

The last specialized test was the determination of the resistance of the concrete surface against the action of water and chemical de-icing agents and was tested on samples older than 28 days due to standard *ČSN 73 1326 Resistance of cement concrete surface to water and defrosting chemicals [25]*. These were cubes with an edge length of 100 mm and 4 cubes of each material were tested. The samples were placed in the testing rig for 100 cycles.

It can be seen from Fig. 17 that the AAM and AAM+L formulations have a similar increase in waste, which is slightly above 3000 g/m^2 after 100 cycles. Significant degradation occurred with the AAM+P recipe, where the resulting waste reaches almost 9000 g/m^2. It is 3 times more than for other recipe variants.

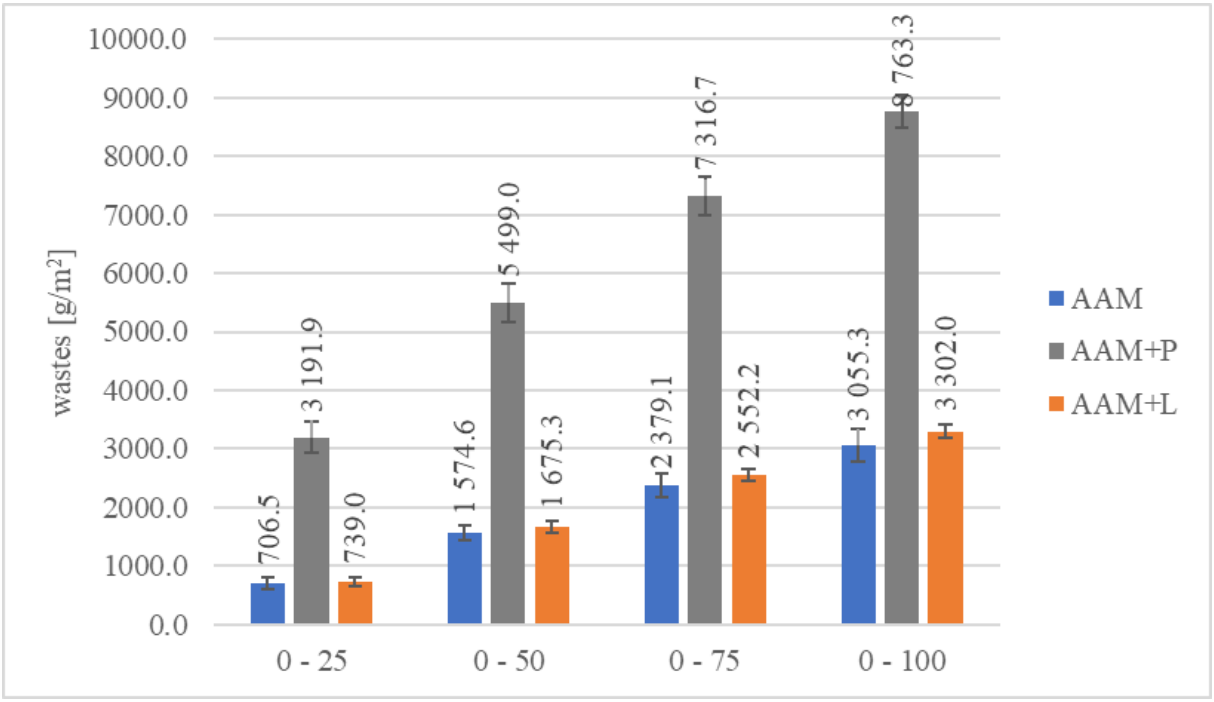


Fig: 17: Comparison of total waste per m^2 between tested materials.

4 Discussion

The comprehensive experimental program provided information on the properties of three different formulas of alkali-activated materials. The results of the experimental program are available in [26]. The AAM samples had after 28 days the highest strengths and the AAM+P samples had the lowest. Split tensile strengths were tested on cubes with an edge length of 150 mm. The highest strength was achieved by the AAM samples (6.20 MPa) and the lowest by the AAM+L samples (4.50 MPa). AAM+P samples had a strength of 4.70 MPa. The dynamic modulus of elasticity was also tested, where it reached the highest value of AAM (32.5 GPa) and the lowest value of AAM+P (27.4 GPa). Furthermore, the effect of increased temperature up to 500°C on mechanical properties was investigated. For all samples, the penetration speed of the ultrasound pulse decreased by almost 50%. The flexural strength also decreased for all materials. The highest strength after exposure in the furnace was achieved by AAM+L (2.0 MPa) and the lowest strength was achieved by AAM (1.8 MPa). Compressive strength also decreased for all materials, with AAM having the highest strength (53.9 MPa) and AAM+P (41.5 MPa) the lowest. It can therefore be said that of these three materials, the material with ash has the worst resistance to high temperatures. In addition, 50 cycle frost resistance test of the alkali-activated composite were performed. The propagation of the ultra-sonic pulse increased in AAM (by 0.01 km/s) and decreased in AAM+L (by 0.02 km/s). Frost resistance had a more pronounced effect on the

penetration speed of the ultra-sonic pulse AAM+P (increase by 0.23 km/s). Flexural strength also increased for all materials. The highest strength after exposure to 500 °C was achieved by AAM (5.2 MPa) and the lowest strength was achieved by AAM+L (4.4 MPa). The compressive strength increased by 19% for AAM, 3% for AAM+L and the compressive strength of AAM+P decreased by 3%. The worst resistance to frost and de-icing chemicals had AAM+P, which had up to three times worse results than the other recipe variants. In all cases, the wastes were very significant.

5 Conclusion

The presented research is devoted to the determination and evaluation of selected mechanical properties of three different recipes of alkali-activated concrete. The first AAM recipe is the basis for two other recipes, which are only modified. AAM+P is modified in that Detmarovice Ash was added instead of 30% of JMŠ 420 blast-furnace slag. For AAM+L, part of the fine aggregate was replaced with lightweight aggregate Liapor 1/4, 500 in the amount of 81 kg per 1 m^3 of the mixture.

In summary, mixture of AAM achieved the best results in all tests, except of test of flexural strength after exposure to high temperatures, when mixture of AAM+P shown a higher flexural strength then mixture of AAM. Using power plant fly ash appears as less ineffective from the results.

It is to be considered with regard to the application solution, when it will be advantageous to use lightweight aggregates, where it is effective to replace 23% of fraction 0/4 aggregate with lightweight Liapor aggregate while reducing the density by only 6% while achieving relatively lower strength-mechanical and durability properties compared to the reference of AAM mixture.

Acknowledgement

This paper was created as part of the project No. CZ.02.01.01/00/22_008/0004631 Materials and technologies for sustainable development within the Jan Amos Komensky Operational Program financed by the European Union and from the state budget of the Czech Republic. This article has been also achieved with the financial support of the Ministry of Education, specifically by the Student Research Grant Competition of the Technical University of Ostrava under identification number SP2023/075.

References

[1] COLLEPARDI, M, 2010 The New Concrete, Grafiche Tintoretto, pp. 436., ISBN 8890377720.HODÁS, S.: Railway track in 3D system. Civil and Environmental Engineering, Vol. 7, Iss. 2, 2011, pp. 121-127.
[2] MATECKOVA, P.- BILEK, V.- SUCHARDA, O. 2021 Comparative Study of High -Performance Concrete Characteristics and Loading Test of Pretensioned Experimental Beams. Crystals 2021, 11, 427. https://doi.org/10.3390/cryst11040427.
[3] Cement Carbon Dioxide Emissions Quietly Double in 20 Years [online]. [2022-10-15]. https://news.wttw.com/2022/06/22/cement-carbon-dioxide-emissionsquietly-double-20-years.
[4] HÁJEK P., 2022. Principles of sustainability in the design of concrete structures according to MC2020, Proceedings of the Conference with international participation 28. CONCRETE DAYS 2022, ČBS. (In Czech: Principy udržitelnosti v navrhování betonových konstrukcí podle MC2020)
[5] JUENGER, M.; WINNEFELD, F.; PROVIS, JL; IDEKER, J. 2011. Advances in alternatives cementitious binders. What. Concr. Res., 41, pp. 1232–1243.
[6] PALOMO A.- GRUTZECK MW- BLANCO MT 1999. Alkali-activated flies ashes: A cement for the future. Cement and Concrete Research, 29 (8), pp. 1323 - 1329, 1999.
[7] PROVIS, J - VAN DEVENTER JSJ 2014. Alkali Acivated Materials. State - of -Art-Report, Rilem TC 224-AAM.
[8] PROVIS, J. 2014 Geopolymers and others alkali activated materials: Why, how, and what? Materials and Structures / Materiaux et Constructions. 47 (1-2), pp. 11-25.
[9] MAKU NATT, 2022 Principles of Cement and Concrete Composites (Structural Integrity) Springer; 1st ed. 2021 Edition (April 2, 2022).
[10] GEMRICH J. - VESELY V. 2023 Low carbon cements 2023, Proceedings of the 18th conference TECHNOLOGY AND IMPLEMENTATION 2023, CBS. (In Czech: Nízkouhlíkové cementy 2023).
[11] PALOMO, A.- MONTEIRO, P.- MARTAUZ, P.- BILEK, V.- FERNANDEZ-JIMENEZ, A. 2019. Hybrid binders: A journey from the past to a sustainable future (opus caementicium futurum) Cement and Concrete Research, 124, art. well 105829, DOI: 10.1016/j.cemconres.2019.105829.
[12] AYDIN, S.- BARADAN, B. 2013. The effects of fiber properties on high performance alkali-activated

slag / silica smoke mortars. Comp. Part B Eng., 45, pp. 63–69.
[13] COLLINS, F. - SANJAYAN, JG 1999. Workability and mechanical properties of alkali activated slag concrete, Cem. Don. Res. 29, pp. 455-458.
[14] GANDEL R., JERABEK J., MARCALIKOVA Z. 2023 Reinforced Concrete Beams Without Shear Reinforcement Using Fiber Reinforced Concrete and Alkali-Activated Material. Civil and Environmental Engineering, 19 (1), pp. 348 - 356, DOI: 10.2478/cee-2023-0031.
[15] AMRAN, M.- FEDIUK, R.- MURALI, G.- AVUDAIAPPAN, S.- OZBAKKALOGLU, T.- VATIN, N.- KARELINA, M.- KLYUEV, S.- GHOLAMPOUR, A. 2021. Fly Ash-Based Eco-Efficient Concretes: A Comprehensive Review of the Short -Term Properties. Materials 2021, 14, 4264.
[16] MOHAMMED, AA- AHMED, HU- MOSAVI, A. 2021. Survey of Mechanical Properties of Geopolymer Concrete: A Comprehensive Review and Data Analysis. Materials 2021, 14, 4690.
[17] SUCHARDA, O.- MARCALIKOVA, Z.- GANDEL, R. 2022 Microstructure, Shrinkage, and Mechanical Properties of Concrete with Fibers and Experiments of Reinforced Concrete Beams without Shear Reinforcement. Materials, 15, 5707, 2022. https://doi.org/10.3390/ma15165707.
[18] BILEK, V.- SUCHARDA, O.- BUJDOS, D. 2021 Frost Resistance of Alkali-Activated Concrete — An Important Pillar of Their Sustainability. Sustainability, 13, 473. https://doi.org/10.3390/su13020473.
[19] NĚMEC, J. 2023 Selected mechanical properties of alkali-activated concrete with regard to processing. Thesis. VSB - Technical University of Ostrava.
[20] ČSN EN 12390-3. Testing hardened concrete – Part 3: Compressive strength of test specimens. Praha: The Czech Office for Standards, Metrology and Testing, 2020.
[21] ČSN EN 12390-5. Testing hardened concrete – Part 5: Flexural strength of test specimens. Praha: The Czech Office for Standards, Metrology and Testing, 2020.
[22] ČSN EN 12390-6. Testing hardened concrete – Part 6: Tensile splitting strength of test specimens. Praha: The Czech Office for Standards, Metrology and Testing, 2010.
[23] ČSN 73 1371. Non-destructive testing of concrete – Method of ultrasonic pulse testing of concrete. Praha: The Czech Office for Standards, Metrology and Testing, 2011.
[24] ČSN 73 1371. Determination of frost resistance of concrete. Praha: The Czech Office for Standards, Metrology and Testing, 1969.
[25] ČSN 73 1326. Resistance of cement concrete surface to water and defrosting chemicals. Praha: The Czech Office for Standards, Metrology and Testing, 1985.
[26] Experimental program data set doi: https://doi.org/10.5281/zenodo.10838526