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**PROPERTIES OF EXPANSIVE POROUS MATERIALS BASED ON ALUMINATE CEMENT FOR UNDERGROUND MINING**

**WŁAŚCIWOŚCI EKSPANSYWNYCH TWORZYW POROWATYCH NA BAZIE CEMENTU GLINOWEGO DLA GÓRNICTWA PODZIEMNEGO**

The paper presents the results of laboratory tests of expansive mineral binding materials based on calcium aluminate with mineral additive and carbonate expander. The expansion size can be controlled by the amount of expander as well as by water-binder ratio. The study describes the method of measuring the expansion size and selected technical parameters of obtained expansive binders together with the proposed scope of their use in underground construction.

**Keywords:** binders, calcium aluminate cement, expander, porosity, compression strength

W artykule zostały przedstawione wyniki badań laboratoryjnych ekspansywnych mineralnych materiałów wiążących na bazie cementów glinowych z dodatkiem mineralnym i ekspansorem węglanowym. Wielkość ekspansji może być regulowana zawartością ekspansora oraz wielkością wskaźnika wodno--spoiwowego. Przedstawiono wybrane parametry techniczne uzyskanych spoiw ekspansywnych oraz możliwe ich zastosowanie w technice górniczej.

**Słowa kluczowe:** spoiwo, cement glinowy, ekspansja, ekspansor, porowatość, wytrzymałość na ściskanie

# 1. Introduction

Technical progress, raw material considerations, ecological and economical reasons make it necessary also in underground mining to modify typical materials or to look for new materials with improved properties. For many years conventional materials have been used, such as lime, cement, composites based on mineral binders or polymers. For some technical solutions that

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include sealing of rocks, connecting the support with rock mass and filling voids in rock mass, it is better not to use a conventional binder but a binder with an adjustable volume expansion, the key characteristics of which are: susceptibility, good penetration and low strength, and such binders may be prepared from commercially available materials. During the increase of volume a slight pressure appaears, which, while the space, ie. between the outline of the heading and the support is being filled, makes the support gain the initial strength and its co-operation with rock mass improves.

In different mining technologies coal mines use mineral binding materials, which are called mineral mining binders (Cevizci, 2014; Chudek et al., 1995; Madaj & Klimas, 2000; Stryczek et al., 2013). They occur in a finely milled (powdery) form and after being mixed with make-up water or an appropriate aqueous solution, as a result of processes taking place between the active ingredients of the binder and water (or aqueous solution), or alternatively with some chemical addition or filler (aggregate), they are capable of binding and hardening , and, as a result, they create a material with the characteristics of a solid body (Neville, 2000; Skalmowski, 1971, 1973; Klimas, 2000). The classification of mineral binders that divides them according to strength increase dynamics and the final strength, that may be used in the mining industry, has been presented in the following works (Hölter, 1992; Matuszewski, 2004; Klimas, 2013). It divides the binders into: immediate supporting, early supporting, late supporting and insulating-filling ones.

This paper presents the results of laboratory tests of the expansive binders with a porous structure, belonging to the class of insulating-filling mineral binders with a low compressive strength, that tightly fill the space into which they are fed. In practice these binders fulfill two objectives: saving of material (binder) and a tight filling of the empty space under the assumption of the increasing volume of binder (expansion). The type of mineral binders used in practice and the scope of their use in underground construction should take into account their physical and mechanical properties and it depends largely on the practical experiences of specific mines. In the modern mining industry mineral binders are necessary for the safe operation of coal mines, being an important component of fire and methane prevention. When deciding on the use of expansive mineral binders, it is necessary to analyze: the choice of binder with specific physico-mechanical properties, its costs, the transport system to the site of binder's application in the mine, the influence of the chosen conveying system to the change of physical and mechanical properties of binder, the efficiency of the equipment, etc. (Klimas, 2013; Madaj & Klimas, 2000; Jahn et al., 2010; Madaj et al., 1997).

The increase of volume or the expansion of mineral binders is a "creation" of a new structure – a "hard" or "soft" one. The so-called "hard" structure, with high compressive strength, occurs with the use of expansive cements, where the increase in volume is caused by the spread over time (weeks, months) formation of salts that increase their volume (expansion of approx. 25 mm/m) (Król, 1999, 2005; Bakhtavar, 2011). The porous structure which is called a "soft-gas" one, and is characterized by a low compressive strength, appears as a result of the rapid (minutes) production of gas that causes scarifying of not yet bound material, and this results in even very large (several dozen percent) increase in the material's volume. In the mining conditions this high expansion rate allows for a tighter filling of voids and it prevents the penetration of gases into the excavation and their accumulation (Janiczek et al., 1980; Klimas, 1995, 2001, 2005, 2007, 2013; Majchrzak & Klimas 2003; Sakwa & Chudek et al., 1987).

With the use of appropriate expanders, as a result of chemical reactions occurring between the components of binders and make-up water, the emission of gas (such as $CO_2$) that scarifies the grout takes place. The extremely important factor is the proper synchronization of binding and expansion processes, providing the appropriate size of the resulting expansion (Sakwa & Chudek et al., 1987; Madaj, 1982; Klimas, 2013). Expansive mineral binders with a "soft" porous structure, in which the volume increase is caused by gas, may be referred to as gas-binders or, depending on the type of binder used, for example as gas-gypsums, gas-concretes (autoclaved concretes based on cement) etc. Expansion of mineral binders changes their apparent density and the resulting materials are more or less porous and have a lower strength in comparison with the same materials without pores.

Laboratory tests were performed to determine the effect of a content and consistency of expander, mineral additive and calcium aluminate cement on the measured final expansion of binder grouts.

## 2. Materials for research

The following materials were used during the laboratory tests: two types of calcium aluminate cements, one with the 40% content of $Al_2O_3$, marked as *L1*, and the other, with 70% content of $Al_2O_3$, marked as *L2*, a gypsum (plaster) based mineral additive *D*, containing calcium sulphate hemihydrate $CaSO_4 \cdot 0{,}5H_2O$, an *E1* carbonate expander (added to the dry ingredients) and tap water, marked as *w*.

The increase of volume, ie. gas expansion of tested mineral binders, was obtained with the use of *E1* carbonate expander, which reaction with the components of grout caused the production of gas and its swelling, which, after hardening, resulted in an porous material of a much larger volume than the initial volume of grout. The *E1* expander has been added and mixed with dry ingredients: calcium aluminate cements *L1*, *L2* and the mineral additive *D*.

## 3. The expansion of mineral binders

The measurements of expansion were conducted by the author with the use of polymethyl methacrylate cylinders, in which the prepared binder grout was placed and the height of fill, ie. the initial level of grout, was marked. Then, after the end of expansion, the maximum level of grout, which is most often the final level of grout, was marked (Klimas, 2010, 2013). In the case of sinking, the final level of the grout did not coincide with the maximum level. The size of expansion was calculated as a percentage, based on formulas:

$$E_{xm} = \frac{V_{xm} - V_O}{V_O} \cdot 100\% \tag{1}$$

$$E_{xk} = \frac{V_{xk} - V_O}{V_O} \cdot 100\% \tag{2}$$

$$E_{xs} = E_{xm} - E_{xk} \tag{3}$$

where:

$V_o$ — initial volume of grout [$dm^3$],

$V_{xm}$ — maximum volume of grout [$dm^3$],

$V_{xk}$ — final volume of grout [$dm^3$],
$E_{xm}$ — maximum expansion of grout [%],
$E_{xk}$ — final expansion of grout [%],
$E_{xs}$ — decrease of expansion [%].

The kind of binder, the amount of make-up water and the content of expander affects both the binding processes and the expansion processes (Sakwa & Chudek et al., 1987; Madaj, 1982; Klimas, 2013).

## 4. The results of laboratory tests

Measurements of the expansion size were carried out on samples containing varying amounts of: *L1* calcium aluminate cement, mineral additive *D*, *E1* expander, and with various water-binder ratios *w/s*. The *L1* and *L2* calcium aluminate cement content ranged from 0 to 100% in relation to the content of mineral additive *D*. The mineral additive *D* content ranged from 0 to 100% in relation to the content of calcium aluminate cement *L1* and *L2*. The *E1* expander was dispensed by weight in relation to the weight of dry ingredients from 0 to 2% in increments of 0,5%. Binder grouts of *L1* or *L2* cement and mineral additive *D* were created with two water-binder ratios *w/s* of 0,5 and 0,6.

First of all the measurements of binder grouts expansion were carried out, with the participation of calcium aluminate cement *L1* with the mineral additive *D* and *E1* expander and with water-binder ratio *w/s* = 0,5; The results are shown in Table 1 and Figure 1.

TABLE 1

The expansion of binder grouts with the participation of calcium aluminate cement *L1* with the mineral additive *D* and *E1* expander with *w/s* = 0,50 ratio

| *L1* [%] | *D* [%] | *w/s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] | *L1* [%] | *D* [%] | *w/s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 0 | 100 | 0,5 | 0,5 | 5,5 | 5,5 | 0,0 | 0 | 100 | 0,5 | 1,5 | 36,9 | 36,9 | 0,0 |
| 10 | 90 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 10 | 90 | 0,5 | 1,5 | 30,3 | 30,3 | 0,0 |
| 20 | 80 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 20 | 80 | 0,5 | 1,5 | 37,5 | 37,5 | 0,0 |
| 30 | 70 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 30 | 70 | 0,5 | 1,5 | 35,2 | 35,2 | 0,0 |
| 40 | 60 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 40 | 60 | 0,5 | 1,5 | 36,3 | 36,3 | 0,0 |
| 50 | 50 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 50 | 50 | 0,5 | 1,5 | 24,2 | 24,2 | 0,0 |
| 60 | 40 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 60 | 40 | 0,5 | 1,5 | 32,7 | 32,7 | 0,0 |
| 70 | 30 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 70 | 30 | 0,5 | 1,5 | 20,5 | 20,5 | 0,0 |
| 80 | 20 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 80 | 20 | 0,5 | 1,5 | 11,1 | 11,1 | 0,0 |
| 90 | 10 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 90 | 10 | 0,5 | 1,5 | 5,4 | 0,0 | 5,4 |
| 100 | 0 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,5 | 1,5 | 0,0 | 0,0 | 0,0 |
| 0 | 100 | 0,5 | 1,0 | 29,5 | 29,5 | 0,0 | 0 | 100 | 0,5 | 2,0 | 42,3 | 42,3 | 0,0 |
| 10 | 90 | 0,5 | 1,0 | 13,9 | 13,9 | 0,0 | 10 | 90 | 0,5 | 2,0 | 41,0 | 41,0 | 0,0 |
| 20 | 80 | 0,5 | 1,0 | 12,4 | 12,4 | 0,0 | 20 | 80 | 0,5 | 2,0 | 46,0 | 46,0 | 0,0 |
| 30 | 70 | 0,5 | 1,0 | 6,3 | 6,3 | 0,0 | 30 | 70 | 0,5 | 2,0 | 73,9 | 73,9 | 0,0 |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 60 | 0,5 | 1,0 | 5,8 | 5,8 | 0,0 | 40 | 60 | 0,5 | 2,0 | 67,8 | 67,8 | 0,0 |
| 50 | 50 | 0,5 | 1,0 | 3,0 | 3,0 | 0,0 | 50 | 50 | 0,5 | 2,0 | 50,2 | 50,2 | 0,0 |
| 60 | 40 | 0,5 | 1,0 | 0,0 | 0,0 | 0,0 | 60 | 40 | 0,5 | 2,0 | 57,4 | 57,4 | 0,0 |
| 70 | 30 | 0,5 | 1,0 | 0,0 | 0,0 | 0,0 | 70 | 30 | 0,5 | 2,0 | 50,4 | 50,4 | 0,0 |
| 80 | 20 | 0,5 | 1,0 | 0,0 | 0,0 | 0,0 | 80 | 20 | 0,5 | 2,0 | 51,4 | 51,4 | 0,0 |
| 90 | 10 | 0,5 | 1,0 | 0,0 | 0,0 | 0,0 | 90 | 10 | 0,5 | 2,0 | 38,4 | 36,0 | 2,4 |
| 100 | 0 | 0,5 | 1,0 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,5 | 2,0 | 0,0 | 0,0 | 0,0 |

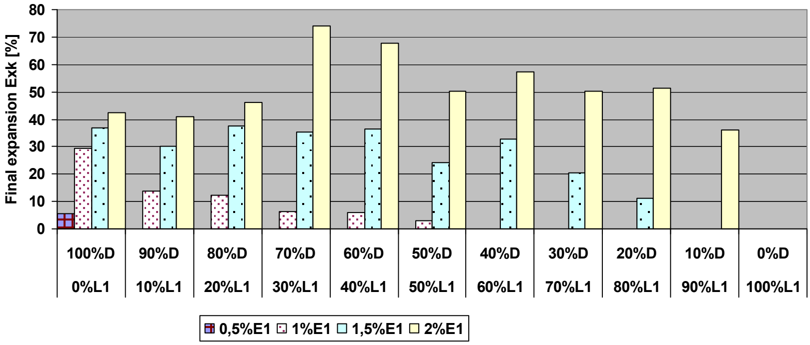


Fig. 1. The relationship of the composition of grouts with calcium aluminate cement *L1* with the mineral additive *D* and *E1* of the size of expansion with *w/s* = 0,50 ratio

The results obtained with water-binder ratio *w/s* = 0,50 (Table 1 and Fig. 1) have shown no expansion of *L1* calcium aluminate cement grouts with mineral additive *D*, with *E1* expander content of 0,5%, with the exception of "pure" mineral additive *D* in an amount of 100%, reaching the final expansion $E_{xk}$ = 5,5%. The increase in an *E1* expander content to 1% resulted in the final expansion $E_{xk}$ of grouts already occurring with the content of mineral additive *D* in an amount of 50% and more, the size of the final expansion $E_{xk}$ ranged from 3% to approx. 14% with the content of *D* = 90%, peaking at $E_{xk}$ = 29,5% with the content of *D* = 100%. With the content of *E1* expander = 1,5% the final expansion $E_{xk}$ already occurred from the mineral additive *D* content = 20%, the size of final expansion $E_{xk}$ ranged from approx. 11% to 37,5% with *D* = 80%, with the *D* content = 100% the final expansion reached approx. $E_{xk} \approx 37\%$. The increase of *E1* expander amount to 2% resulted in the final expansion $E_{xk}$ of grouts already appeared with 10% content of mineral additive *D*, and the size of final expansion $E_{xk}$ ranged from approx. 36% to a maximum of approx. 74% reached with a 70% of *D* mineral additive content, with the amount of *D* = 100% the final expansion reached approx. $E_{xk} \approx 42\%$. The expansion of calcium aluminate cement *L1* = 100% has not occurred despite the use of expander *E1* in the range of 0,5% to 2,0%. The sinking of expanding grouts $E_{xs}$ was observed with the *E1* expander content of 1,5% and 2,0%, with 10% amount of mineral additive *D*. Next the measurements of binder grouts expansion with the participation of calcium aluminate cement *L1*, with mineral additive *D* and *E1* expander, and with water-binder ratio *w/s* = 0,6 were carried out; The results are presented in Table 2 and Figure 2.

TABLE 2

The expansion of binder grouts with the participation of calcium aluminate cement *L1* with the mineral additive *D* and *E1* expander with *w/s* = 0,60 ratio

| *L1* [%] | *D* [%] | *w/s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] | *L1* [%] | *D* [%] | *w/s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 0 | 100 | 0,6 | 0,5 | 2,8 | 2,8 | 0,0 | 0 | 100 | 0,6 | 1,5 | 27,9 | 27,9 | 0,0 |
| 10 | 90 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 10 | 90 | 0,6 | 1,5 | 28,2 | 28,2 | 0,0 |
| 20 | 80 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 20 | 80 | 0,6 | 1,5 | 45,0 | 45,0 | 0,0 |
| 30 | 70 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 30 | 70 | 0,6 | 1,5 | 33,5 | 33,5 | 0,0 |
| 40 | 60 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 40 | 60 | 0,6 | 1,5 | 26,9 | 26,9 | 0,0 |
| 50 | 50 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 50 | 50 | 0,6 | 1,5 | 22,8 | 22,8 | 0,0 |
| 60 | 40 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 60 | 40 | 0,6 | 1,5 | 11,7 | 10,5 | 1,2 |
| 70 | 30 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 70 | 30 | 0,6 | 1,5 | 12,1 | 10,9 | 1,3 |
| 80 | 20 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 80 | 20 | 0,6 | 1,5 | 7,4 | 6,1 | 1,3 |
| 90 | 10 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 90 | 10 | 0,6 | 1,5 | 3,7 | 0,0 | 3,7 |
| 100 | 0 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,6 | 1,5 | 0,0 | 0,0 | 0,0 |
| 0 | 100 | 0,6 | 1,0 | 8,2 | 8,2 | 0,0 | 0 | 100 | 0,6 | 2,0 | 31,8 | 31,8 | 0,0 |
| 10 | 90 | 0,6 | 1,0 | 9,0 | 9,0 | 0,0 | 10 | 90 | 0,6 | 2,0 | 45,4 | 43,8 | 1,6 |
| 20 | 80 | 0,6 | 1,0 | 14,0 | 14,0 | 0,0 | 20 | 80 | 0,6 | 2,0 | 55,5 | 55,5 | 0,0 |
| 30 | 70 | 0,6 | 1,0 | 8,9 | 8,9 | 0,0 | 30 | 70 | 0,6 | 2,0 | 63,6 | 63,6 | 0,0 |
| 40 | 60 | 0,6 | 1,0 | 5,0 | 5,0 | 0,0 | 40 | 60 | 0,6 | 2,0 | 67,7 | 67,7 | 0,0 |
| 50 | 50 | 0,6 | 1,0 | 2,5 | 2,5 | 0,0 | 50 | 50 | 0,6 | 2,0 | 45,5 | 45,5 | 0,0 |
| 60 | 40 | 0,6 | 1,0 | 0,0 | 0,0 | 0,0 | 60 | 40 | 0,6 | 2,0 | 52,3 | 52,3 | 0,0 |
| 70 | 30 | 0,6 | 1,0 | 1,3 | 0,0 | 1,3 | 70 | 30 | 0,6 | 2,0 | 40,2 | 38,0 | 2,2 |
| 80 | 20 | 0,6 | 1,0 | 8,7 | 0,0 | 4,4 | 80 | 20 | 0,6 | 2,0 | 41,7 | 41,7 | 0,0 |
| 90 | 10 | 0,6 | 1,0 | 0,0 | 0,0 | 0,0 | 90 | 10 | 0,6 | 2,0 | 30,4 | 0,0 | 30,4 |
| 100 | 0 | 0,6 | 1,0 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,6 | 2,0 | 0,0 | 0,0 | 0,0 |

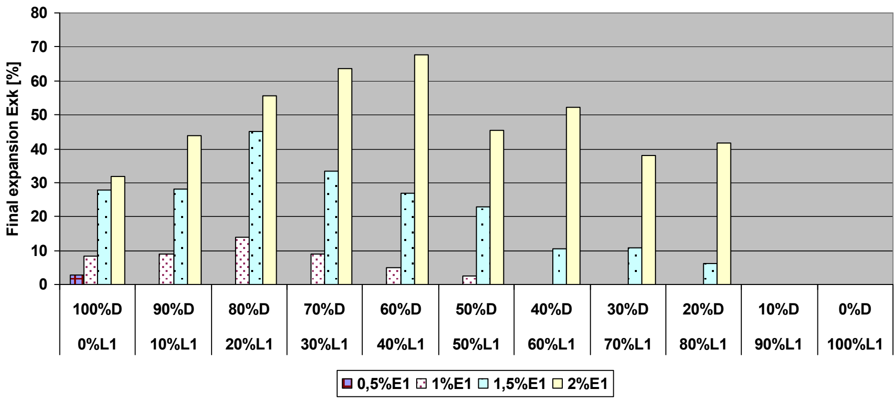


Fig. 2. The relationship of the composition of grouts with calcium aluminate cement *L1* with the mineral additive *D* and *E1* of the size of expansion with *w/s* = 0,60 ratio

The results with water-binder ratio *w/s* = 0,60 (Table 2 and Fig. 2) have shown no expansion of calcium aluminate cement grouts with 0,5% of *E1* expander content, with mineral additive *D*, except for the "pure" mineral additive *D* in an amount of 100%, reaching the final expansion $E_{xk}$ = 2,8%. When the *E1* expander content = 1% the final expansion of grouts $E_{xk}$ already occured with the mineral additive *D* content of 50% and more, and the final $E_{xk}$ expansion size began from 2,5%, reaching a maximum $E_{xk}$ = 14% with a content of *D* = 80%; with the content of *D* = 100% the final expansion reached approx. $E_{xk} \approx 8\%$. With the content of *E1* expander = 1,5% the final expansion $E_{xk}$ already occurred with the mineral additive *D* content of 20% and more, and the size of the final expansion $E_{xk}$ began from 6,1% to a maximum of $E_{xk}$ = 45% with a content of *D* = 80%, with the content of *D* = 100% the final expansion reached approx. $E_{xk} \approx 28\%$. With the increase of *E1* expander content to 2% the final expansion of grouts $E_{xk}$ appeared also with the mineral additive *D* content of 20%, and the size of final expansion $E_{xk}$ ranged from approx. 42% to a maximum of approx. 68% with the mineral additive *D* content of 60%, with the *D* content = 100% the final expansion reached approx. $E_{xk} \approx 32\%$. The expansion of calcium aluminate cement *L1* = 100% has not occurred despite the use of *E1* expander in the range of 0,5% to 2,0%. The sinking of expanding grouts $E_{xs}$ was observed in several cases from $E_{xs}$ = 1,3% for *D* = 30% and *E1* = 1,0%, to the highest value of $E_{xs}$ = 30,4% with *E1* expander content of 2,0%, and with the mineral additive *D* content of 10%.

The measurements of binder grouts expansion with the second type of calcium aluminate cement *L2* were conducted, with the mineral additive *D* and with *E1* expander, and water-binder ratio *w/s* = 0,5; The results are shown in Table 3 and Figure 3.

TABLE 3

The expansion of binder grouts with the participation of calcium aluminate cement *L2* with the mineral additive *D* and *E1* expander with *w/s* = 0,50 ratio

| *L2* [%] | *D* [%] | *w/s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] | *L2* [%] | *D* [%] | *w/s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 0 | 100 | 0,5 | 0,5 | 5,5 | 5,5 | 0,0 | 0 | 100 | 0,5 | 1,5 | 36,9 | 36,9 | 0,0 |
| 10 | 90 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 10 | 90 | 0,5 | 1,5 | 44,4 | 44,4 | 0,0 |
| 20 | 80 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 20 | 80 | 0,5 | 1,5 | 35,6 | 35,6 | 0,0 |
| 30 | 70 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 30 | 70 | 0,5 | 1,5 | 22,5 | 22,5 | 0,0 |
| 40 | 60 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 40 | 60 | 0,5 | 1,5 | 24,1 | 24,1 | 0,0 |
| 50 | 50 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 50 | 50 | 0,5 | 1,5 | 24,5 | 24,5 | 0,0 |
| 60 | 40 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 60 | 40 | 0,5 | 1,5 | 51,2 | 51,2 | 0,0 |
| 70 | 30 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 70 | 30 | 0,5 | 1,5 | 42,0 | 42,0 | 0,0 |
| 80 | 20 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 80 | 20 | 0,5 | 1,5 | 45,6 | 45,6 | 0,0 |
| 90 | 10 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 90 | 10 | 0,5 | 1,5 | 8,8 | 8,8 | 0,0 |
| 100 | 0 | 0,5 | 0,5 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,5 | 1,5 | 0,0 | 0,0 | 0,0 |
| 0 | 100 | 0,5 | 1,0 | 29,5 | 29,5 | 0,0 | 0 | 100 | 0,5 | 2,0 | 42,3 | 42,3 | 0,0 |
| 10 | 90 | 0,5 | 1,0 | 15,0 | 15,0 | 0,0 | 10 | 90 | 0,5 | 2,0 | 48,9 | 48,9 | 0,0 |
| 20 | 80 | 0,5 | 1,0 | 14,4 | 14,4 | 0,0 | 20 | 80 | 0,5 | 2,0 | 41,7 | 41,7 | 0,0 |
| 30 | 70 | 0,5 | 1,0 | 12,0 | 12,0 | 0,0 | 30 | 70 | 0,5 | 2,0 | 38,9 | 38,9 | 0,0 |
| 40 | 60 | 0,5 | 1,0 | 10,2 | 10,2 | 0,0 | 40 | 60 | 0,5 | 2,0 | 46,2 | 46,2 | 0,0 |
| 50 | 50 | 0,5 | 1,0 | 11,8 | 11,8 | 0,0 | 50 | 50 | 0,5 | 2,0 | 56,2 | 56,2 | 0,0 |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60 | 40 | 0,5 | 1,0 | 10,9 | 10,9 | 0,0 | 60 | 40 | 0,5 | 2,0 | 66,3 | 66,3 | 0,0 |
| 70 | 30 | 0,5 | 1,0 | 11,3 | 11,3 | 0,0 | 70 | 30 | 0,5 | 2,0 | 48,3 | 48,3 | 0,0 |
| 80 | 20 | 0,5 | 1,0 | 11,6 | 11,6 | 0,0 | 80 | 20 | 0,5 | 2,0 | 65,4 | 65,4 | 0,0 |
| 90 | 10 | 0,5 | 1,0 | 5,8 | 5,8 | 0,0 | 90 | 10 | 0,5 | 2,0 | 74,7 | 0,0 | 74,7 |
| 100 | 0 | 0,5 | 1,0 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,5 | 2,0 | 0,0 | 0,0 | 0,0 |

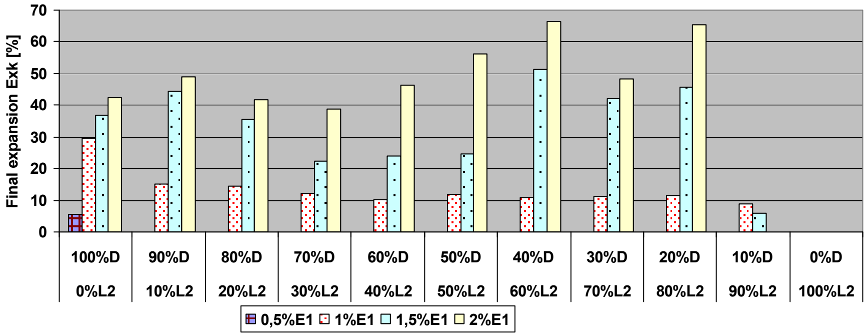


Fig. 3. The relationship of the composition of grouts with calcium aluminate cement *L2* with the mineral additive *D* and *E1* of the size of expansion with *w/s* = 0,50 ratio

The results with water-binder ratio *w/s* = 0,50 (Table 3 and Fig. 3) showed no expansion of *L1* calcium aluminate cement grouts with *E1* expander content of 0,5% and with a mineral additive *D*, except for the "pure" mineral additive *D* in an amount of 100%, reaching the final expansion $E_{xk}$ =5,5%. With the *E1* expander content = 1% the final expansion of grouts $E_{xk}$ occured form the mineral additive *D* content of 10% and more, and the size of the final expansion began from $E_{xk}$ of approx. 6% to a maximum of $E_{xk}$ = 15% with a content of *D* = 90%, with the content of *D* = 100% the final expansion reached approx. $E_{xk} \approx$ 30%. With the *E1* expander content = 1,5% the final expansion $E_{xk}$ occurred with the mineral additive *D* content of 10% and more, and the size of the final expansion $E_{xk}$ began at 8,8%, reaching a maximum $E_{xk}$ = 44% with a content of *D* = 90%, with the content of *D* = 100% the final expansion reached approx. $E_{xk} \approx$ 37%. With the increase of the *E1* expander content to 2% the final expansion of grouts $E_{xk}$ appeared with the mineral additive *D* content of 20%, and the size of final expansion $E_{xk}$ ranged from approx. 42% to a maximum of approx. 66% with the mineral additive *D* content of 40%, with a content of *D* = 100% the final expansion reached approx. $E_{xk}$ = 49%. The expansion of calcium aluminate cement *L1* = 100% has not occurred despite the use of *E1* expander in the range of 0,5% to 2,0%. The sinking of expanding grouts $E_{xs}$ was observed for *D* = 10% and *E1* = 2,0%, reaching a value of approx. $E_{xs} \approx$ 75%.

The expansion measurements of binder grouts with the participation of calcium aluminate cement *L2*, the mineral additive *D* and *E1* expander, with water-binder ratio *w/s* = 0,6 were carried out next; the results are shown in Table 4 and Figure 4.

TABLE 4

The expansion of binder grouts with the participation of calcium aluminate cement *L2* with the mineral additive *D* and *E1* expander with *w*/*s* = 0,60 ratio

| *L2* [%] | *D* [%] | *w*/*s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] | *L2* [%] | *D* [%] | *w*/*s* | *E1* [%] | $E_{xm}$ [%] | $E_{xk}$ [%] | $E_{xs}$ [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 0 | 100 | 0,6 | 0,5 | 2,8 | 2,8 | 0,0 | 0 | 100 | 0,6 | 1,5 | 27,9 | 27,9 | 0,0 |
| 10 | 90 | 0,6 | 0,5 | 1,2 | 1,2 | 0,0 | 10 | 90 | 0,6 | 1,5 | 34,3 | 34,3 | 0,0 |
| 20 | 80 | 0,6 | 0,5 | 2,4 | 2,4 | 0,0 | 20 | 80 | 0,6 | 1,5 | 43,5 | 43,5 | 0,0 |
| 30 | 70 | 0,6 | 0,5 | 3,9 | 3,9 | 0,0 | 30 | 70 | 0,6 | 1,5 | 32,6 | 32,6 | 0,0 |
| 40 | 60 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 40 | 60 | 0,6 | 1,5 | 47,4 | 47,4 | 0,0 |
| 50 | 50 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 50 | 50 | 0,6 | 1,5 | 41,1 | 41,1 | 0,0 |
| 60 | 40 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 60 | 40 | 0,6 | 1,5 | 55,3 | 55,3 | 0,0 |
| 70 | 30 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 70 | 30 | 0,6 | 1,5 | 53,3 | 47,4 | 5,9 |
| 80 | 20 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 80 | 20 | 0,6 | 1,5 | 49,7 | 44,7 | 5,0 |
| 90 | 10 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 90 | 10 | 0,6 | 1,5 | 7,0 | 4,5 | 2,5 |
| 100 | 0 | 0,6 | 0,5 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,6 | 1,5 | 0,0 | 0,0 | 0,0 |
| 0 | 100 | 0,6 | 1,0 | 8,2 | 8,2 | 0,0 | 0 | 100 | 0,6 | 2,0 | 31,8 | 31,8 | 0,0 |
| 10 | 90 | 0,6 | 1,0 | 20,5 | 20,5 | 0,0 | 10 | 90 | 0,6 | 2,0 | 57,0 | 57,0 | 0,0 |
| 20 | 80 | 0,6 | 1,0 | 21,1 | 21,1 | 0,0 | 20 | 80 | 0,6 | 2,0 | 62,2 | 62,2 | 0,0 |
| 30 | 70 | 0,6 | 1,0 | 9,9 | 9,9 | 0,0 | 30 | 70 | 0,6 | 2,0 | 55,5 | 55,5 | 0,0 |
| 40 | 60 | 0,6 | 1,0 | 11,1 | 11,1 | 0,0 | 40 | 60 | 0,6 | 2,0 | 59,3 | 59,3 | 0,0 |
| 50 | 50 | 0,6 | 1,0 | 9,7 | 9,7 | 0,0 | 50 | 50 | 0,6 | 2,0 | 74,0 | 74,0 | 0,0 |
| 60 | 40 | 0,6 | 1,0 | 12,7 | 12,7 | 0,0 | 60 | 40 | 0,6 | 2,0 | 66,9 | 66,9 | 0,0 |
| 70 | 30 | 0,6 | 1,0 | 7,5 | 6,2 | 1,3 | 70 | 30 | 0,6 | 2,0 | 71,9 | 47,5 | 24,4 |
| 80 | 20 | 0,6 | 1,0 | 13,6 | 13,6 | 0,0 | 80 | 20 | 0,6 | 2,0 | 67,5 | 5,5 | 62,0 |
| 90 | 10 | 0,6 | 1,0 | 5,0 | 1,3 | 3,8 | 90 | 10 | 0,6 | 2,0 | 52,2 | 0,0 | 52,2 |
| 100 | 0 | 0,6 | 1,0 | 0,0 | 0,0 | 0,0 | 100 | 0 | 0,6 | 2,0 | 0,0 | 0,0 | 0,0 |

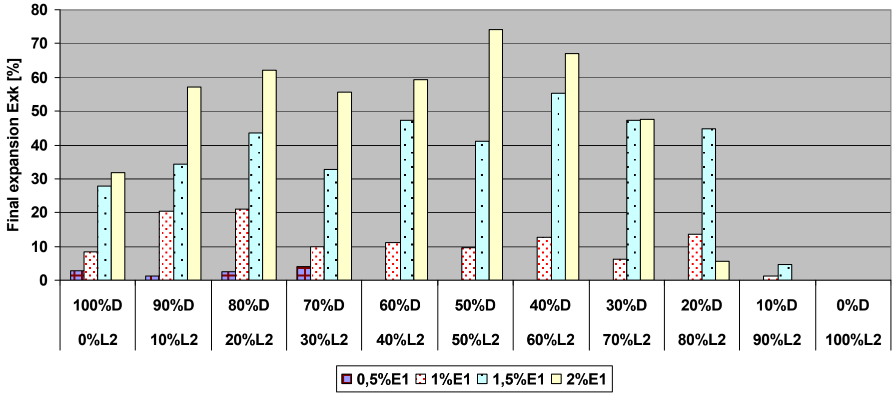


Fig. 4. The relationship of the composition of grouts with calcium aluminate cement *L2* with the mineral additive *D* and *E1* of the size of expansion with *w*/*s* = 0,60 ratio

The results with water-binder ratio $w/s$ = 0,60 (Table 4 and Fig. 4) have shown no expansion of *L1* calcium aluminate cement grouts with *E1* expander content of 0,5% and with a mineral additive *D*, except for the "pure" mineral additive *D* in an amount of 100% reaching the final expansion $E_{xk}$ = 2,8%. With the *E1* expander content = 1% the final expansion of grouts $E_{xk}$ occurred with the mineral additive *D* content of 10% and more, and the size of the final expansion $E_{xk}$ began at approx. 1% to a maximum of $E_{xk}$ = 21% with a content of *D* = 80%, with a content of *D* = 100% the final expansion reached approx. $E_{xk} \approx$ 8%. With the *E1* expander content = 1,5% the final expansion $E_{xk}$ occurred with the mineral additive *D* content of 10% and more, and the size of the final expansion $E_{xk}$ began with approx. 5% to a maximum $E_{xk}$ = 74% with a content of *D* = 40%, with the content of *D* = 100% the final expansion reached approx. $E_{xk} \approx$ 32%. With the increase of *E1* expander amount to 2% the final expansion $E_{xk}$ of grouts appeared with the mineral additive *D* content of 20%, and the size of final expansion $E_{xk}$ ranged from approx. 6% to a maximum of approx. 66% with the mineral additive *D* content of 50%, with a *D* content = 100%, the final expansion reached approx. $E_{xk} \approx$ 32%. The expansion of calcium aluminate cement *L1* = 100% has not occurred despite the use of *E1* expander in the range of 0,5% to 2,0%. The sinking of expanding grouts $E_{xs}$ was observed in several cases, from $E_{xs}$ = 1,0% to $E_{xs}$ = 62%.

Due to the fact that calcium aluminate cements *L1* and *L2* do not differ in strength and apparent density, one type of cement was used to determine the dynamics of compressive strength development $R_c$ in time *t* and an apparent density of samples, and it is the *L1* calcium aluminate cement. The strength determinations were made on samples stored in air-dry conditions after 1, 3 and 7 days. The results of the compressive strength and the size of expansion determinations, as well as apparent densities of the hardened grouts with water-binder ratio $w/s$ = 0,50 and different contents of *E1* expander, are presented in Table 5 and Figures 5 and 6.

TABLE 5

Selected properties of grouts with the participation of calcium aluminate cement *L1* with the mineral additive *D* and *E1* expander with $w/s$ = 0,50 ratio

| ***D*** | ***L1*** | ***E1*** | ***w/s*** | **Compressive strength $R_c$** | | | **Apparent density $\rho_p$** | **$E_{xk}$** |
|---|---|---|---|---|---|---|---|---|
| | | | | **1d** | **3d** | **7d** | | |
| **[%]** | **[%]** | **[%]** | | **[MPa]** | **[MPa]** | **[MPa]** | **[Mg/m$^3$]** | **[%]** |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| 100 | 0 | 0,0 | 0,50 | 5,63 | 3,63 | 12,69 | 1,567 | 0,0 |
| 100 | 0 | 0,5 | 0,50 | 2,06 | 1,63 | 2,94 | 1,403 | 5,5 |
| 100 | 0 | 1,0 | 0,50 | 0,94 | 0,69 | 3,38 | 1,265 | 29,5 |
| 100 | 0 | 1,5 | 0,50 | 0,44 | 0,63 | 2,19 | 1,144 | 36,9 |
| 100 | 0 | 2,0 | 0,50 | 0,19 | 0,25 | 2,00 | 1,077 | 42,3 |
| 60 | 40 | 0,0 | 0,50 | 12,94 | 18,94 | 23,61 | 1,699 | 0,0 |
| 60 | 40 | 0,5 | 0,50 | 3,57 | 8,02 | 8,56 | 1,580 | 2,4 |
| 60 | 40 | 1,0 | 0,50 | 1,58 | 4,80 | 5,87 | 1,380 | 7,3 |
| 60 | 40 | 1,5 | 0,50 | 0,88 | 2,27 | 3,03 | 1,104 | 36,3 |
| 60 | 40 | 2,0 | 0,50 | 0,51 | 1,70 | 1,20 | 0,942 | 62,8 |

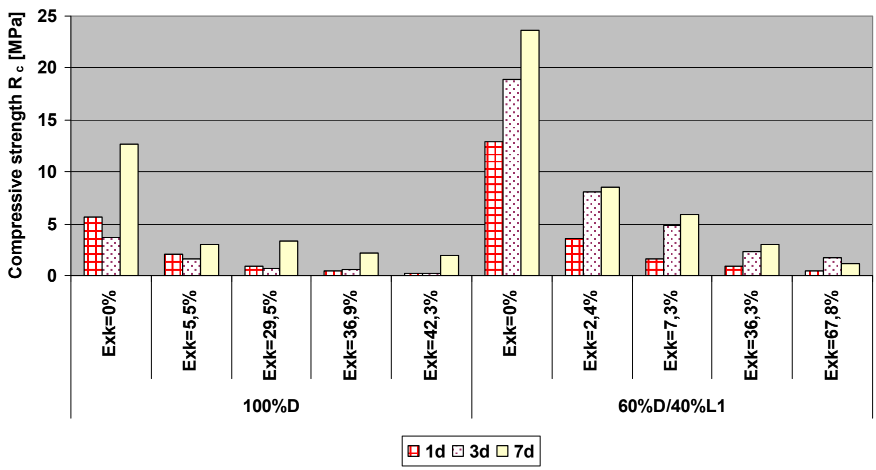


Fig. 5. The relationship between composition of grouts and compressive strength $R_c$ and final expansion $E_{xk}$ with $w/s$ = 0,50 ratio

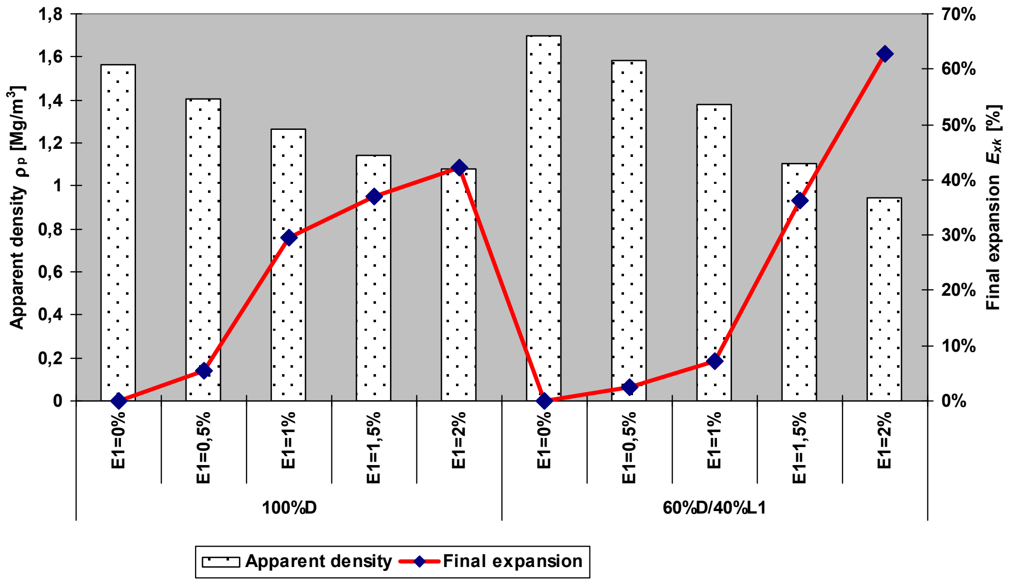


Fig. 6. The relationship between composition of grouts and apparent density $\rho_p$ and final expansion $E_{xk}$ with $w/s$ = 0,50 ratio

The results of compressive strength and the size of expansion determinations, as well as the apparent densities of the hardened grouts with a $w/s$ = 0,60 and different contents of *E1* expander, are presented in Table 6 and Figures 7 and 8.

TABLE 6

Selected properties of grouts with the participation of calcium aluminate cement *L1* with the mineral additive *D* and *E1* expander with *w/s* = 0,60 ratio

| *D* | *L1* | *E1* | w/s | Compressive strength $R_c$ | | | Apparent density $\rho_p$ | $E_{xk}$ |
|---|---|---|---|---|---|---|---|---|
| | | | | 1d | 3d | 7d | | |
| [%] | [%] | [%] | | [MPa] | [MPa] | [MPa] | [Mg/m$^3$] | [%] |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 100 | 0 | 0,0 | 0,60 | 3,63 | 2,44 | 10,19 | 1,499 | 0,0 |
| 100 | 0 | 0,5 | 0,60 | 1,13 | 1,13 | 4,16 | 1,407 | 2,8 |
| 100 | 0 | 1,0 | 0,60 | 0,50 | 0,25 | 1,69 | 1,114 | 8,2 |
| 100 | 0 | 1,5 | 0,60 | 0,13 | 0,09 | 1,06 | 0,945 | 27,9 |
| 100 | 0 | 2,0 | 0,60 | 0,09 | 0,06 | 0,81 | 0,823 | 31,8 |
| 60 | 40 | 0,0 | 0,60 | 6,57 | 7,95 | 11,11 | 1,575 | 0,0 |
| 60 | 40 | 0,5 | 0,60 | 2,54 | 4,76 | 3,84 | 1,428 | 1,8 |
| 60 | 40 | 1,0 | 0,60 | 1,39 | 3,41 | 3,41 | 1,320 | 5,0 |
| 60 | 40 | 1,5 | 0,60 | 0,25 | 1,64 | 1,64 | 0,986 | 26,9 |
| 60 | 40 | 2,0 | 0,60 | 0,06 | 0,57 | 0,63 | 0,770 | 67,7 |

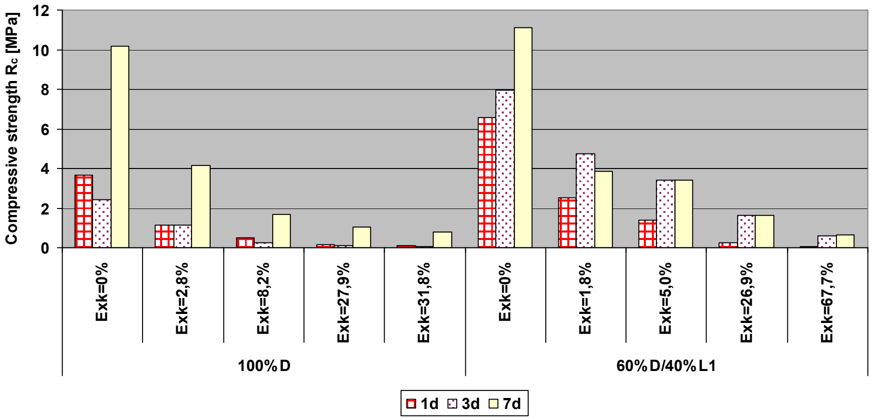


Fig. 7. The relationship between composition of grouts and compressive strength $R_c$ and final expansion $E_{xk}$ with *w/s* = 0,60 ratio

## 5. Recapitulation

The paper presents the results of laboratory tests that allow for specifying the following conclusions:

1. Laboratory tests have shown that mineral binders (binder grouts) based on calcium aluminate cements, after appropriate chemical activation, have the ability to swell (expand) creating as a result a porous material of increased volume and specific physical and mechanical properties.
2. The size of expansion depends on the composition of binder, the amount of expander, *w/s* ratio, and the proper synchronization of expansion time with binding time.

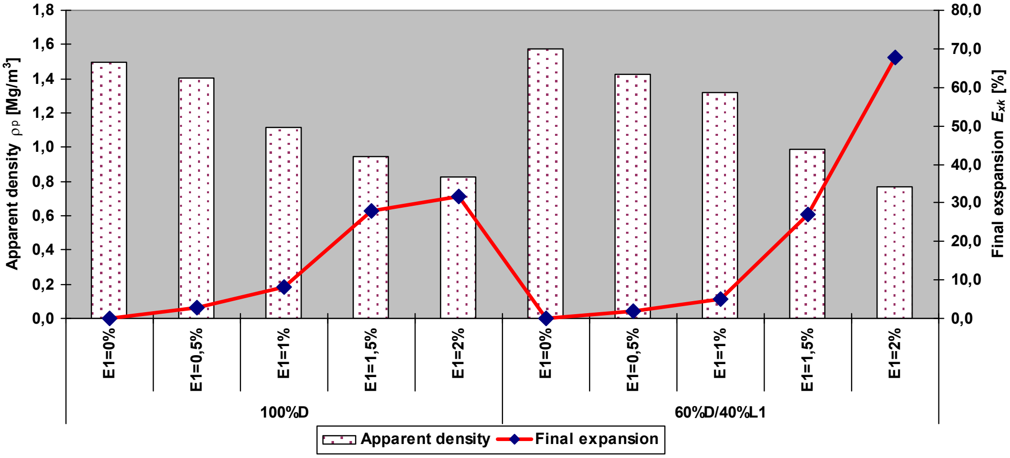


Fig. 8. The relationship between composition of grouts and apparent density $\rho_p$ and final expansion $E_{xk}$ with $w/s$ = 0,60 ratio

3. The apparent density $\rho_p$ of the examined expansive binders based on calcium aluminate cements ranged from 0,77 Mg/m$^3$ to 1,58 Mg/m$^3$, depending on the amount of expander and water-binder ratio.
4. In the case of higher content of calcium aluminate cement and *E1* expander, the sinking of grouts and the reduction of final expansion in relation to maximum expansion $E_{xk} < E_{xm}$ was observed.
5. The presence of voids in the form of pores in the hardened grout of expansive binder based on calcium aluminate cement provides a material with very good insulation and thermal insulation properties and a low compressive strength.
6. The compressive strength of porous expansive binders is inversely proportional to their apparent density and final expansion $E_{xk}$.
7. The properties of *L1* and *L2* expansive mineral binders based on calcium aluminate cements are similar and do not essentially differ from each other.
8. Due to their properties, expansive binders may be used in underground construction for: filling rifts and voids in rock mass, making insulating and heat insulating shotcrete, sealing the goaf of longwalls with cavings, caulking insulating plugs, etc.

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