Efficiency Assessment of Accelerating Admixtures and Cement Kiln Dust with Cooperation with Different Phase Composition Slag Blended Cements

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Abstract. Concrete technology involves nowadays several types of chemical admixtures. One of them is setting and hardening accelerating admixtures. Main benefits of their usage are enhancement of early compressive strength and shortening of initial setting time. Unfortunately, they may cause decrease of long-term compressive strength and adversely influence durability properties of concrete. Slag blended cements with 30% and 60% of slag content were used. Ground granulated blast furnace slag (GGBFS) that is main non-clinker constituent of those cements is beneficially changing its properties. It favourably affecting long-term compressive strength, consistency and durability properties of concrete. Main drawback of slag blended cements are decrease of early compressive strength and extension of initial setting time. Both accelerating admixtures and ground granulated blast furnace slag have advantages and disadvantages that may be at least partially balanced. Slag blended cements were composed in laboratory conditions of three Portland clinkers, differing in phase composition, anhydrite as set regulating constituent and ground granulated blast furnace slag in amount of 30% and 60% of Portland clinker mass. Cements was modified with accelerating admixtures with crystal seeds and calcium nitrate as active agent and cement kiln dust in amount of 10% of the cements mass. During previous research crystal seeds and calcium nitrate were examined with CEM I, CEM II/B-S and CEM III/A, B, manufactured by one of polish cement plants. Calcium nitrate acts mainly on dicalcium and tricalcium silicate (C2S and C3S). Crystal seeds are acting physically on all cements phases by means of acceleration of C-S-H phase formation by faster crystallisation. Their performance may be similar independently on cement phase composition. Aim of this paper is to describe effectiveness of those admixtures in cooperation with CEM II/B and CEM III/A, differing in phase composition. Additionally, cements were modified with Cement Kiln Dust (CKD) and their properties were tested. Such dusts may accelerate setting and hardening of cement because of chloride and carbonate content, which are constituents of accelerating admixtures. In addition, their form of very fine powder may allow them to act similarly to crystal seeds. Initial setting time, consistency and compressive strength of mortars were examined. Tests were conducted in temperature of 20°C. Compressive strength was tested after 12, 24, 48 hours and 7, 28 and 90 days of curing in temperature 20°C in water. In most works those properties are considered separately. In order to determine efficiency of substances mentioned above the multiple-criteria decision analysis (MCDA) was made for every kind of cement. This kind of analysis allows to take examined properties as set of properties and give information about the behaviour of admixture and cement cooperation in more general terms. Criteria were defined on the basis of conducted tests and their weights were evaluated with pair
analysis method. Admixture with crystal seeds was most efficient one, while Cement Kiln Dust was the least efficient.

1. Introduction
Modern concrete technology involves modifications with chemical admixtures. In many regions, such as USA, Western Europe, Australia or Japan, modified concrete production constitutes for majority of concrete production. In Central Europe this amount is lower but still raising. The most popular types of admixtures are plasticizers and superplasticizers, air entraining agents and accelerating admixtures [1, 2].

Main benefits of accelerating admixtures usage are enhancement of early compressive strength and shortening of initial setting time. Those properties give possibility of earlier demoulding of precast and monolithic elements, quicker form rotation, elongation of construction season, especially in regions with temperate and cold climate and higher cost efficiency of concrete works [1-4]. Unfortunately, they may cause decrease of long-term compressive strength and adversely influence durability properties of concrete [1-3]. A lot of research deal with traditional accelerators as calcium nitrate, calcium formate, calcium chloride, etc. and their beneficial and adverse influence on concrete. During last decade some new solutions appeared. Such modern types of accelerating admixtures for concrete are agents acting as crystallization seeds [5-7], or physically on the cement grains’ surface [8]. They are proved to be efficient and deprived of disadvantages of traditional accelerators in cooperation with Portland cement.

Cement Kiln Dust (CKD) are highly alkaline. Their pH is about 12. They contain sodium and potassium hydroxides, that accelerate compressive strength of slag blended cements gain by decomposition of glass phase of slag [9]. Cement Kiln Dust contain the same components as Portland clinker in different proportions that are very fine. Its specific surface area is in range 4000 – 14000 cm²/g. Thanks to that CKD are more reactive. Very important constituents of Cement Kiln Dust are chlorides and carbonates that are used as active substances in accelerating admixtures. Also cement pastes incorporating Cement Kiln Dust are less porous [10-14].

Modern accelerators’ and Cement Kiln Dust efficiency is described in cooperation with Portland cement mainly. Nowadays however concrete production deals with significant amount of mineral additives, such as fly ash, ground granulated blast furnace slag or silica fume. Such additives allow to decrease costs of concrete manufacturing and constructions erecting and lower the impact on environment of cement and concrete production [1,15]. Ground granulated blast furnace slag (GGBFS) that is main non-clinker constituent of cements CEM II/A, B-S, CEM III and CEM V and is beneficially changing their properties. It beneficially affecting consistency of concrete mix, long-term compressive strength and durability properties of concrete. Main disadvantages of slag blended cements are decrease of early compressive strength and extension of initial setting time [1,15].

2. Experimental

2.1. Range and target
Initial setting time, consistency and compressive strength of mortars were examined. Tests were conducted in temperature of 20°C. Compressive strength was tested after 12, 24, 48 hours and 7, 28 and 90 days of curing in temperature 20°C in water. In most works those properties are considered separately. In order to determine efficiency of substances mentioned above the multiple-criteria decision analysis (MCDA) was made for every kind of cement. This kind of analysis allows to take examined properties as set of properties and give information about the behavior of admixture and cement cooperation in more general terms.
2.2. Materials

Cements containing different amounts of ground granulated blast furnace slag (GGBFS) were prepared in laboratory - CEM II/B-S with 35% of GGBFS and blast furnace cement CEM III/A with 65% of GGBFS. Cements were prepared with three different Portland clinkers, varying in phase composition, ground granulated blast furnace slag and anhydrite as setting regulator. Amount of regulator was established to obtain 2% of $\text{SO}_3$ in resulting cements. Specific surface area of clinkers was 3000 cm$^2$/g and of slag 3870 cm$^2$/g. Chemical composition of clinkers is given in table 1, their phase composition and characteristic modules in table 2. Chemical composition of anhydrite and ground granulated blast furnace slag are given in tables 3 and 4 respectively. Exact compositions of cements used for tests are given in table 6.

### Table 1. Chemical composition of Portland clinkers.

|   | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | Cl$^-$ | Na$_2$O | K$_2$O | Na$_2$O$_{eq}$ | CaO$_{free}$ | ign. loss | non. solv. |
|---|---------|-------------|-------------|-----|-----|-------|-------|--------|-------|--------------|--------------|-----------|-----------|
| C1| 20.25   | 6.83        | 3.23        | 65.66| 1.39| 0.69  | 0.01  | 0.15   | 1.02  | 0.82         | 2.80         | 0.15      | 0.52      |
| C2| 21.25   | 5.00        | 3.40        | 64.81| 2.09| 0.55  | 0.03  | 0.11   | 1.03  | 0.79         | 1.48         | 0.35      | 0.67      |
| C3| 21.62   | 4.58        | 5.75        | 65.38| 1.79| 0.27  | 0.01  | 0.30   | 0.25  | 0.46         | 0.95         | 0.25      | 0.46      |

### Table 2. Phase composition and modules of Portland clinkers.

|   | C$_2$S | C$_3$S | C$_3$A | C$_4$AF | Lime saturation factor (LSF) | Silica modulus (SR) | Alumina Ratio (AR) |
|---|--------|--------|--------|---------|-----------------------------|---------------------|-------------------|
| C1| 10.90  | 64.40  | 13.50  | 7.30    | 0.88                        | 2.01                | 2.11              |
| C2| 12.43  | 68.68  | 14.06  | 12.14   | 0.90                        | 2.53                | 1.48              |
| C3| 18.26  | 57.95  | 2.39   | 17.48   | 0.90                        | 2.09                | 0.80              |

### Table 3. Chemical composition of anhydrite.

|   | SiO$_2$ | CaO | MgO | SO$_3$ | Na$_2$O | ign. loss |
|---|---------|-----|-----|-------|--------|-----------|
| Anhydrite| 0.61 | 40.16 | 0.40 | 54.83 | 0.02 | 2.71      |

### Table 4. Chemical composition of ground granulated blast furnace slag.

|   | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | Cl$^-$ | Na$_2$O | K$_2$O | Na$_2$O$_{eq}$ | CaO$_{free}$ | ign. loss |
|---|---------|-------------|-------------|-----|-----|-------|-------|--------|-------|--------------|--------------|-----------|
| GGBFS| 37.35   | 7.30        | 1.22        | 43.90| 5.73| 0.62  | 0.03  | 0.55   | 0.56  | 0.92         | 0.17         |           |

Three types of accelerators were involved. First is one of the modern solutions. It is accelerating admixture that contains crystal seeds (CS). This admixture is described by producer as both set and hardening accelerating admixture. It was added in amount of 4% of cement mass. Second used agent is water solution of calcium nitrate (CN). Concentration of solution was 10% and it was added into water in amount resulting in 2% of calcium nitrate according to cement mass. Admixtures were added to water in maximal amount allowed by producers. Third accelerator used during research was Cement Kiln Dust (CKD) in amount of 10% of cement mass. Its chemical composition is given in table 5.

### Table 5. Chemical composition of Cement Kiln Dust.

|   | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | Cl$^-$ | Na$_2$O | K$_2$O | Na$_2$O$_{eq}$ | CaO$_{free}$ | ign. Loss. | n.solv. |
|---|---------|-------------|-------------|-----|-----|-------|-------|--------|-------|--------------|--------------|-----------|---------|
| CKD| 18.24   | 4.83        | 2.33        | 56.63| 1.56| 2.02  | 1.40  | 0.39   | 3.66  | 2.80         | 15.90        | 10.30     | 2.01    |
Table 6. Composition of cements.

| Symbol        | Clinker | C1  | 63.40 | 34.14 | 2.46 |
|---------------|---------|-----|-------|-------|------|
| CEM II (C1)   | C2      | 63.29| 34.08 | 2.63  |
| CEM II (C3)   | C3      | 63.08| 33.97 | 2.95  |
| CEM III (C1)  | C1      | 34.13| 63.37 | 2.50  |
| CEM III (C2)  | C2      | 34.09| 63.32 | 2.59  |
| CEM III (C3)  | C3      | 34.03| 63.20 | 2.77  |
| CEM II (C1)+CKD | C1  | 57.06| 30.72 | 2.22  | 10.00|
| CEM II (C2)+CKD | C2  | 56.96| 30.67 | 2.37  | 10.00|
| CEM II (C3)+CKD | C3  | 56.77| 30.57 | 2.66  | 10.00|
| CEM III (C1)+CKD | C1  | 30.71| 57.04 | 2.25  | 10.00|
| CEM III (C2)+CKD | C2  | 30.69| 56.98 | 2.33  | 10.00|
| CEM III (C3)+CKD | C3  | 30.63| 60.01 | 2.49  | 10.00|

Mortars were prepared with water-cement ratio equal to 0.5 and CEN-Standard sand was used according to EN 196-1. Composition of mortars for consistency and compressive strength tests is given in table 7. For initial setting time tests amount of water was determined by standard consistency test performed with Vicat apparatus.

Table 7. Composition of mortars.

| Symbol               | cement | sand  | water | admixture |
|----------------------|--------|-------|-------|-----------|
| M II (Cx)            | 450    | 1350  | 225   | -         |
| M II (Cx)+CS         |        |       |       | CS 4% c.m.|
| M II (Cx)+CN         |        |       |       | CN 2% c.m.|
| M III (Cx)           |        |       |       | -         |
| M III (Cx)+CS        |        |       |       | CS 4% c.m.|
| M III (Cx)+CN        |        |       |       | CN 2% c.m.|
| M II (Cx)+CKD        |        |       |       | -         |
| M III (Cx)+CKD       |        |       |       | -         |

2.3. Methods

Range of the report consists of results from consistency of mortars, initial setting time of cement and compressive strength of mortars tests. Specimens for all tests were prepared in temperature 20±1°C. Mortar specimens for compressive strength were made in temperature of 20±1°C and were cured in water until the test was conducted. Examinations were conducted according to European Standards:

- EN 196-1:2016-07 Methods of testing cement. Determination of strength.
• EN 196-3:2016-12 Methods of testing cement - Part 3: Determination of setting times and soundness.
• EN 1015-3:1999 Methods of test for mortar for masonry. Determination of consistency of fresh mortar (by flow table).

For determination of effectiveness relations multiple-criteria decision analysis (MCDA) was made for every kind of cement. Criteria were defined on the basis of conducted tests and their weights were evaluated with pair analysis method.

3. Results and discussions

3.1. Initial setting time
Initial setting time tests were conducted. Results are given in table 8. All used accelerators have caused decrease of initial setting time for both cements with all Portland clinkers. Effectiveness of crystal seeds based accelerator (CS) is the highest. Lowest decrease of initial setting time was observed for Cement Kiln Dust modified cements.

| Mortar symbol | Spread diameter [cm] | Initial setting time [min] | Compressive strength [MPa] |
|---------------|----------------------|----------------------------|---------------------------|
| M II (C1)     | 11,3                 | 165                        | 12 hours 24 hours 48 hours 7 days 28 days 90 days |
| M II (C2)     | 17,5                 | 235                        | 2,8 5,5 11,4 22,0 45,2 53,5 |
| M II (C3)     | 20,0                 | 250                        | 0,0 2,0 7,8 20,1 41,1 50,2 |
| M II (C1)+CS  | 22,0                 | 110                        | 3,5 7,8 14,9 23,6 46,5 57,6 |
| M II (C2)+CS  | 20,5                 | 125                        | 4,6 14,0 20,8 27,1 42,9 49,7 |
| M II (C3)+CS  | 23,0                 | 160                        | 0,8 3,9 9,6 22,2 44,1 60,2 |
| M II (C1)+CN  | 16,5                 | 140                        | 3,7 8,4 14,1 26,9 46,2 58,3 |
| M II (C2)+CN  | 19,5                 | 165                        | 6,0 12,7 21,5 30,7 44,9 50,7 |
| M II (C3)+CN  | 22,0                 | 150                        | 0,6 3,0 10,0 21,8 41,9 55,8 |
| M II (C1)+CKD | 16,5                 | 140                        | 3,7 6,7 13,6 23,7 39,5 49,2 |
| M II (C2)+CKD | 19,5                 | 175                        | 3,6 12,4 21,1 29,6 42,4 47,6 |
| M II (C3)+CKD | 21,5                 | 205                        | 0,5 2,8 8,3 24,5 43,1 54,4 |
| M III (C1)    | 18,0                 | 235                        | 1,1 3,1 5,0 13,1 38,3 57,1 |
| M III (C2)    | 19,5                 | 295                        | 1,0 3,8 8,0 19,9 40,8 50,1 |
| M III (C3)    | 21,0                 | 330                        | 0,0 1,3 5,0 15,4 38,6 52,7 |
| M III (C1)+CS | 25,0                 | 145                        | 1,7 3,6 7,3 19,1 46,5 58,2 |
| M III (C2)+CS | 23,0                 | 190                        | 1,8 4,9 8,6 21,3 38,9 49,7 |
| M III (C3)+CS | 25,0                 | 240                        | 0,9 2,5 6,1 17,4 42,5 55,0 |
| M III (C1)+CN | 20,5                 | 180                        | 1,4 3,8 5,8 15,0 47,9 57,7 |
| M III (C2)+CN | 21,0                 | 200                        | 0,9 4,0 9,3 20,3 39,8 54,0 |
| M III (C3)+CN | 22,0                 | 225                        | 0,5 1,9 5,3 16,0 40,2 54,9 |
| M III (C1)+CKD| 20,0                 | 145                        | 1,2 4,7 6,2 16,1 37,6 44,5 |
| M III (C2)+CKD| 21,5                 | 200                        | 1,0 4,9 9,0 23,0 37,4 47,6 |
| M III (C3)+CKD| 22,5                 | 285                        | 0,4 1,5 6,9 17,3 35,9 48,3 |

3.2. Spread diameter
Final spread diameters of mortars are shown in table 8. Admixtures with crystal seeds (CS) caused increase of CEM II/B-S and CEM III/A mortars’ spread diameter in comparison to reference mortars.
Effect of calcium nitrate and Cement Kiln Dust modification of cement is also profitable in terms of consistency enhancement but in lower degree.

3.3. Compressive strength
All of tested accelerators have enhanced the compressive strength in early terms (12 – 24 h). Although strength of modified mortars differs accordingly to cement and clinker type. It is not possible to determine which accelerator is the most efficient in compressive strength enhancement accordingly to which Portland clinker was used to prepare cement. Only Cement Kiln Dust has caused decrease of compressive strength after 28 and 90 days. Crystal seeds and calcium nitrate have beneficial influence on long-term compressive strength.

3.4. Multiple-criteria decision analysis
For determination of effectiveness relations multiple-criteria decision analysis (MCDA) was made for every kind of cement. Process of the multiple-criteria decision analysis (MCDA) is as follows:

1. Determination of analysis target,
2. Determination of criteria,
3. Determination of criteria’s weights,
4. Data processing,
5. Choice of optimal variant.

The first step is determination of analysis objective. As mentioned it is to compare accelerators for concrete with regards to both initial setting time shortening and compressive strength of mortars increase. The second step is to create criteria list according to which accelerators are to be graded. Because it is better to obtain shorter initial setting time those criteria are dampers and because it is better to obtain enhanced workability and greater compressive strength those criteria are both boosters. Final set of criteria is given in table 9.

| Symbol | Criteria                                      | Type of criterion |
|--------|-----------------------------------------------|-------------------|
| K1     | Initial setting time                          | Damper           |
| K2     | Spread diameter                               | Booster          |
| K3     | Compressive strength of mortars after 12 hours| Booster          |
| K4     | Compressive strength of mortars after 24 hours| Booster          |
| K5     | Compressive strength of mortars after 48 hours| Booster          |
| K6     | Compressive strength of mortars after 7 days  | Booster          |
| K7     | Compressive strength of mortars after 28 days | Booster          |
| K8     | Compressive strength of mortars after 90 days | Booster          |

The third step settling criteria weights. It was done with pair analysis method. It was conducted by preforming of the m x m matrix, where m is number of criteria. Then the sum in each row was calculated and was divided by number of criteria (m). Values of matrix elements were calculated by formula (1).

\[
a_{ij} = \begin{cases} 
1, & \text{when } i \text{ criterion is more significant than criterion } j \\
0, & \text{otherwise} 
\end{cases} 
\]  

Resultant matrix of weights, sum of rows and sum of rows divided by number of criteria (m) is shown below:
Data were processed using Newman-Morgenstern method. It is used to convert tests results into dimensionless quantities from range [0,1]. Following formulas for boosters (3) and for dampers (4) are used for this purpose.

\[
    z_j = \frac{x_j - x_{j,\text{min}}}{x_{j,\text{max}} - x_{j,\text{min}}} \quad (3)
\]

\[
    z_j = \frac{x_{j,\text{max}} - x_{j}}{x_{j,\text{max}} - x_{j,\text{min}}} \quad (4)
\]

Next coded values are multiplied by weights of criteria to obtain resultant and then resultants are to be summed to obtain final result using formula (5).

\[
    J_i = \sum_{j=1}^{m} (z_{ij} \cdot v_j) \quad (5)
\]

Final part of MCDA is analysis and ordering of the results. Detailed calculations are given in tables 10 – 15. In case of both cements CEM II/B-S and CEM III/A, the accelerator based on crystal seeds (CS) is the best solution in according to chosen criteria. The second one is calcium nitrate based one (CN). The lowest results were obtained for cement modified with Cement Kiln Dust (CKD).

### Table 10. Mean and coded values and resultant for CEM II/B-S with C1 Portland clinker.

| Cement’s symbol | K1  | K2  | K3  | K4  | K5  | K6  | K7  | K8  | Sum |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| **Mean values** |     |     |     |     |     |     |     |     |      |
| M II (C1)+CS    | 110 | 22  | 3,5 | 7,8 | 14,9| 23,6| 46,5| 57,6|      |
| M II (C1)+CN    | 140 | 16,5| 3,7 | 8,4 | 14,1| 26,9| 46,2| 58,3|      |
| M II (C1)+CKD   | 140 | 16,5| 3,7 | 6,7 | 13,6| 23,7| 39,5| 49,2|      |
| **Weight of criteria** |     |     |     |     |     |     |     |     |      |
| M II (C1)+CS    | 0,88| 0,00| 0,75| 0,63| 0,5 | 0,38| 0,25| 0,13|      |
| M II (C1)+CN    | 1,00| 1,00| 0,00| 0,65| 1,00| 0,00| 1,00| 0,92|      |
| M II (C1)+CKD   | 0,00| 0,00| 1,00| 0,00| 0,03| 0,00| 0,00| 0,00|      |
| **Coded values** |     |     |     |     |     |     |     |     |      |
| M II (C1)+CS    | 0,00| 0,00| 1,00| 1,00| 0,38| 1,00| 0,96| 1,00|      |
| M II (C1)+CN    | 0,00| 0,00| 0,00| 0,41| 0,50| 0,00| 0,25| 0,12| 2,16 |
| M II (C1)+CKD   | 0,88| 0,00| 0,75| 0,63| 0,19| 0,38| 0,24| 0,13| 2,32 |
| **Resultant**   |     |     |     |     |     |     |     |     |      |
| M II (C1)+CS    | 0,00| 0,00| 0,75| 0,00| 0,00| 0,01| 0,00| 0,00| 0,76 |
### Table 11. Mean and coded values and resultant for CEM II/B-S with C2 Portland clinker.

| Cement’s symbol          | Criteria |  |  |  |  |  |  |  |
|--------------------------|----------|---|---|---|---|---|---|---|
| M II (C2)+CS             | K1       | 125 | 20,5 | 4,6 | 14 | 20,8 | 27,1 | 42,9 | 49,7 |
| M II (C2)+CN             | K2       | 165 | 19,5 | 6   | 12,7 | 21,5 | 30,7 | 44,9 | 50,7 |
| M II (C2)+CKD            | K3       | 175 | 19,5 | 3,6 | 12,4 | 21,1 | 29,6 | 42,4 | 47,6 |

**Mean values**

| Cement’s symbol          | K4       | 0,88 | 0,00 | 0,75 | 0,63 | 0,5 | 0,38 | 0,25 | 0,13 |
|--------------------------|----------|------|------|------|------|-----|-----|-----|-----|
| M II (C2)+CS             | K5       | 1,00 | 1,00 | 0,42 | 1,00 | 0,00 | 0,00 | 0,20 | 0,68 |
| M II (C2)+CN             | K6       | 0,20 | 0,00 | 1,00 | 0,19 | 1,00 | 1,00 | 1,00 | 1,00 |
| M II (C2)+CKD            | K7       | 0,88 | 0,00 | 0,31 | 0,63 | 0,00 | 0,00 | 0,05 | 0,09 |
| **Resultant**            | K8       | **1,96** | **2,30** | **0,48** |

### Table 12. Mean and coded values and resultant for CEM II/B-S with C3 Portland clinker.

| Cement’s symbol          | Criteria |  |  |  |  |  |  |  |  |
|--------------------------|----------|---|---|---|---|---|---|---|---|
| M II (C2)+CS             | K1       | 160 | 23 | 0,8 | 3,9 | 7,3 | 19,1 | 44,1 | 60,2 |
| M II (C2)+CN             | K2       | 150 | 22 | 0,6 | 3 | 10 | 21,8 | 41,9 | 55,8 |
| M II (C2)+CKD            | K3       | 205 | 21,5 | 0,5 | 2,8 | 8,3 | 24,5 | 43,1 | 54,4 |

**Mean values**

| Cement’s symbol          | K4       | 0,88 | 0,00 | 0,75 | 0,63 | 0,5 | 0,38 | 0,25 | 0,13 |
|--------------------------|----------|------|------|------|------|-----|-----|-----|-----|
| M II (C2)+CS             | K5       | 0,82 | 1,00 | 1,00 | 1,00 | 0,76 | 0,15 | 1,00 | 1,00 |
| M II (C2)+CN             | K6       | 1,00 | 0,33 | 0,33 | 0,18 | 1,00 | 0,00 | 0,00 | 0,24 |
| M II (C2)+CKD            | K7       | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 1,00 | 0,55 | 0,00 |
| **Resultant**            | K8       | **2,92** | **1,78** | **0,52** |

### Table 13. Mean and coded values and resultant for CEM III/B-S with C1 Portland clinker.

| Cement’s symbol          | Criteria |  |  |  |  |  |  |  |  |
|--------------------------|----------|---|---|---|---|---|---|---|---|
| M III (C1)+CS            | K1       | 145 | 25 | 1,7 | 3,6 | 7,3 | 19,1 | 46,5 | 58,2 |
| M III (C1)+CN            | K2       | 180 | 20,5 | 1,4 | 3,8 | 5,8 | 15 | 47,9 | 57,7 |
| M III (C1)+CKD           | K3       | 145 | 20 | 1,2 | 4,7 | 6,2 | 16,1 | 37,6 | 44,5 |

**Mean values**

| Cement’s symbol          | K4       | 0,88 | 0,00 | 0,75 | 0,63 | 0,5 | 0,38 | 0,25 | 0,13 |
|--------------------------|----------|------|------|------|------|-----|-----|-----|-----|
| M III (C1)+CS            | K5       | 1,00 | 1,00 | 1,00 | 0,00 | 1,00 | 1,00 | 0,86 | 1,00 |
| M III (C1)+CN            | K6       | 0,00 | 0,10 | 0,40 | 0,18 | 0,00 | 0,00 | 1,00 | 0,96 |
| M III (C1)+CKD           | K7       | 1,00 | 0,00 | 0,00 | 1,00 | 0,27 | 0,27 | 0,00 | 0,00 |
| **Resultant**            | K8       | **2,86** | **0,79** | **1,75** |
Table 14. Mean and coded values and resultant for CEM III/B-S with C2 Portland clinker.

| Cement’s symbol | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 |
|-----------------|----|----|----|----|----|----|----|----|
| M III (C2)+CS   | 190| 23 | 21 | 4,9| 8,6| 21,3| 38,9| 49,7|
| M III (C2)+CN   | 200| 21 | 0,9| 4  | 9,3| 20,3| 39,8| 54  |
| M III (C2)+CKD  | 200| 21,5|1  | 4,9| 9  | 23  | 37,4| 47,6|

| Weight of criteria | 0,88 | 0,00 | 0,75 | 0,63 | 0,5 | 0,38 | 0,25 | 0,13 |
|-------------------|------|------|------|------|-----|------|------|------|
| M III (C2)+CS     | 1,00 | 1,00 | 1,00 | 1,00 | 0,00 | 0,37 | 0,63 | 0,33 |
| M III (C2)+CN     | 0,00 | 0,00 | 0,00 | 0,00 | 1,00 | 0,00 | 1,00 | 1,00 |
| M III (C2)+CKD    | 0,00 | 0,25 | 0,11 | 1,00 | 0,57 | 1,00 | 0,00 | 0,00 |
| M III (C2)+CS     | 0,88 | 0,00 | 0,75 | 0,63 | 0,00 | 0,14 | 0,16 | 0,04 |

| Coded values      | M III (C2)+CS | 0,75 | 1,00 | 0,75 | 0,00 | 0,50 | 0,00 | 0,50 |
|-------------------|----------------|------|------|------|------|------|------|------|
| M III (C2)+CN     | 1,00 | 0,00 | 0,20 | 0,40 | 0,00 | 0,00 | 0,65 | 0,99 |
| M III (C2)+CKD    | 0,88 | 0,00 | 0,15 | 0,25 | 0,00 | 0,00 | 0,16 | 0,13 |
| M III (C2)+CS     | 0,66 | 0,00 | 0,75 | 0,63 | 0,25 | 0,38 | 0,25 | 0,13 |

| Resultant         | M III (C2)+CS | 0,66 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
|-------------------|----------------|------|------|------|------|------|------|------|
| M III (C2)+CN     | 0,88 | 0,00 | 0,15 | 0,25 | 0,00 | 0,00 | 0,16 | 0,13 |
| M III (C2)+CKD    | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,35 | 0,00 | 0,00 |

Table 15. Mean and coded values and resultant for CEM III/B-S with C3 Portland clinker.

| Cement’s symbol | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 |
|-----------------|----|----|----|----|----|----|----|----|
| M III (C3)+CS   | 240| 25 | 0,9| 2,5| 6,1| 17,4| 42,5| 55  |
| M III (C3)+CN   | 225| 22 | 0,5| 1,9| 5,3| 16  | 40,2| 54,9|
| M III (C3)+CKD  | 285| 22,5|0,4| 1,5| 6,9| 17,3| 35,9| 48,3|

| Weight of criteria | 0,88 | 0,00 | 0,75 | 0,63 | 0,5 | 0,38 | 0,25 | 0,13 |
|-------------------|------|------|------|------|-----|------|------|------|
| M III (C3)+CS     | 0,75 | 1,00 | 1,00 | 1,00 | 0,50 | 1,00 | 1,00 | 1,00 |
| M III (C3)+CN     | 1,00 | 0,00 | 0,20 | 0,40 | 0,00 | 0,00 | 0,65 | 0,99 |
| M III (C3)+CKD    | 0,66 | 0,00 | 0,75 | 0,63 | 0,25 | 0,38 | 0,25 | 0,13 |

| Coded values      | M III (C3)+CS | 0,75 | 1,00 | 0,75 | 0,00 | 0,50 | 1,00 | 1,00 |
|-------------------|----------------|------|------|------|------|------|------|------|
| M III (C3)+CN     | 1,00 | 0,00 | 0,20 | 0,40 | 0,00 | 0,00 | 0,65 | 0,99 |
| M III (C3)+CKD    | 0,88 | 0,00 | 0,15 | 0,25 | 0,00 | 0,00 | 0,16 | 0,13 |
| M III (C3)+CS     | 0,66 | 0,00 | 0,75 | 0,63 | 0,25 | 0,38 | 0,25 | 0,13 |

| Resultant         | M III (C3)+CS | 0,75 | 1,00 | 0,75 | 0,00 | 0,50 | 1,00 | 1,00 |
|-------------------|----------------|------|------|------|------|------|------|------|
| M III (C3)+CN     | 1,00 | 0,00 | 0,20 | 0,40 | 0,00 | 0,00 | 0,65 | 0,99 |
| M III (C3)+CKD    | 0,88 | 0,00 | 0,15 | 0,25 | 0,00 | 0,00 | 0,16 | 0,13 |

4. Conclusions

All of the accelerators have shortened initial setting time. The most effective accelerators in shortening of initial setting time are those based on crystal seeds (CS) and calcium nitrate (CN). Crystal seeds admixture (CS) has slightly better performance. Cement Kiln Dust (CKD) caused lower shortening of initial setting time in case of all cements.

All of tested accelerators have enhanced the compressive strength in early terms. Although strength of modified mortars differs accordingly to cement and clinker type. It is not possible to determine which accelerator is the most efficient in compressive strength enhancement accordingly to which Portland clinker was used to prepare cement.

Only Cement Kiln Dust has caused decrease of compressive strength after 28 and 90 days.

Multi-criteria decision analysis (MCDA) have shown that accelerator with calcium nitrate (CN) is the most effective taking into account both initial setting time and compressive strength for Portland slag cement CEM II/B-S in cooperation with Portland clinkers with higher C3S content and crystal seeds (CS) based accelerator in cooperation with Portland clinker with lower C3S content. The lowest results were obtained for Cement Kiln Dust (CKD) modified cements CEM II/B-S.

Multi-criteria decision analysis (MCDA) have shown that accelerator with crystal seeds (CS) is the most effective taking into account both initial setting time and compressive strength for blast furnace
cement CEM III/A independently on which Portland clinker was used. The second modifier is Cement Kiln Dust in cooperation with Portland clinkers with higher C_3S content and calcium nitrate (CN) based accelerator in cooperation with Portland clinker with lower C_3S content.

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