Comparison of Efficiency of Accelerating Admixtures for Concrete Using Multiple-Criteria Decision Analysis (MCDA)

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Abstract. A lot of different types of accelerating admixtures for concrete are used nowadays. The aim of this paper is to determine efficiency relations between several accelerating admixtures for concrete with usage of multiple-criteria decision analysis (MCDA). Tests of cements’ initial setting time, consistency and compressive strength of mortars were made. Tests of cements and fresh mortars were conducted in temperature 8°C and 20°C. Compressive strength were tested after 12, 24, 48 hours and 7, 28 days of curing. Specimens for those tests were cured in temperature 8°C in water and 20°C in climatic chamber with relative humidity 60%. Mortars were made of Portland cement (CEM I 52,5R), Portland-slag cement (CEM II/B-S) and two kinds of blast furnace cement (CEM III/A, CEM III/C). Examined admixtures were based on calcium formate, crystal seeds and calcium nitrate. All of them are described as both set and hardening accelerators for concrete. Admixtures were added in maximum dosage allowed by producer. All of admixtures caused decrease of initial setting time and increase of early compressive strength (12-48 hours) with varying degrees. Decrease of 28 days compressive strength was not noted in case of any admixture. In order to determination of efficiency relations the multiple-criteria decision analysis (MCDA) was made for every kind of cement separately. Criteria were defined on the basis of conducted tests and were divided accordingly to environmental conditions. Weights of criteria were evaluated with pair analysis method. Values of tests’ results were converted with usage of Neuman-Morgenstern method. Result of analysis is sum of criteria evaluations according to their weights. Accelerating admixture based on crystal seeds in proven to be the most efficient one, while the one based on calcium formate is the least efficient of tested admixtures.

1. Introduction
Nowadays most ready-mix concrete and precast elements production involves chemical admixtures. In many countries modified concrete production states for majority of total concrete production. Examples of such countries are USA, Australia and Japan. In Central Europe region this fraction is lower although is still increasing. The most popular types of admixtures are water reducing, air entraining and accelerating agents [1].

Usage of accelerators for concrete is substantial for obtaining high early strength and gives possibility of quicker form rotation in the precast plants, shorter duration of formworks rental and elongation of construction season [1, 2]. Many papers describe calcium formate as the second most efficient, after calcium chloride, agent in terms of set and hardening acceleration of concrete [1, 2, 3]. Although alternative solutions were developed during last ten years [4, 5, 6, 7]. Examples of modern types of accelerators are those which introduce crystal seeds [4, 5, 6] into concrete mix or acts physically on the
cement grains’ surface [7]. Some of traditional accelerators may cause enhanced shrinkage of concrete and lower corrosion resistance and long-term compressive strength of concrete [1, 2]. There are few publications dealing with those admixtures, and most of them proves their efficiency with cooperation with Portland cement. Although significant percentage of concrete production involves also mineral additives, accordingly to sustainable trends in construction sector [1, 8]. This group consists of fly ash, ground granulated blast furnace slag, etc.

Additives allow to decrease cost of concrete and perform constructions in more environmental friendly way [1, 8]. Beside that their presence in concrete help improvement of rheological, mechanical and durability properties. Ground granulated blast furnace slag (GGBFS) improves corrosion resistance, workability and long-term compressive strength of concrete [1, 8]. Although it decreases hydration heat evolution of cement and early compressive strength of concrete and increases initial setting time of cement [1, 8]. Hence simultaneous usage of accelerators and GGBFS may be profitable in terms of efficient construction of concrete elements and structures.

2. Experimental

2.1. Range and target

Most of researchers show action of accelerators in terms of their influence on different properties of concrete separately. This article is an attempt to compare effectiveness of different accelerating admixtures (calcium formate, calcium nitrate and crystal seeds) taking into account initial setting time of cements and compressive strength of mortars altogether. Such approach is possible with usage of multiple-criteria decision analysis (MCDA).

2.2. Materials

Cements containing different amounts of ground granulated blast furnace slag (GGBFS) were used. Reference mixes were made of Portland cement (CEM I 52,5R). Tested cements were also Portland-slag cement (CEM II/B-S with 35% of GGBFS) and two blast furnace cements (CEM III/A with 65% of GGBFS and CEM III/C with 95% of GGBFS). Blaine’s specific surface of Portland cement was 4230 [cm²/g] and of GGBFS it was 4230 [cm²/g].

Three types of accelerating admixtures were involved. All of them are described by producers as set and hardening accelerating admixtures. First of them is based on calcium formate (CF), which is reported to be most efficient accelerator besides calcium chloride [2]. It may cause enhanced shrinkage of concrete but does not cause extensive corrosion risk. Second is one of the modern solutions. It contains crystal seeds (CS). Third’s chemical base is calcium nitrate (CN). Characteristics of those agents are given in table 1. Admixtures were added to water in maximal amount allowed by producers.

Specimens were made with water-binder ratio equal to 0.5. Amount of water was decreased by amount of water present in accelerating admixtures. Dry masses of those agents are given in table 1. CEN-Standard sand was used according to EN 196-1.

Composition of mortars for compressive strength tests is given in table 2. For initial setting time tests amount of water was determined by standard consistency test performed with Vicat apparatus.

Table 1. Accelerating admixtures characteristics

| Symbol | Chemical base     | General action | Range of dosage [% c.m.] | Dry mass [%] |
|--------|-------------------|----------------|--------------------------|--------------|
| CF     | Calcium formate   | SAA, HAA       | 0.2 – 5.0                | 50           |
| CS     | Crystal seeds     | SAA, HAA       | 2.0 – 4.0                | 20           |
| CN     | Calcium nitrate   | SAA, HAA       | 1.0 – 3.0                | < 5          |
### Table 2. Composition of mortars

| Symbol | Cement type | Admixture | Mortars | Cement [g] | Water [g] | Sand [g] | Admixture [% c.m.] |
|--------|-------------|-----------|---------|------------|-----------|----------|-------------------|
| I      | CEM I 52,5R | -         | 450.0   | 225.0      | 0.0       | 1350.0   |                   |
| II     | CEM II/B-S  | -         |         | 225.0      | 0.0       |          |                   |
| III/A  | CEM III/A   | -         |         | 225.0      | 0.0       |          |                   |
| III/C  | CEM III/C   | -         |         | 225.0      | 0.0       |          |                   |
| I CF   | CEM I 52,5R | CF        |         | 202.5      | 5.0       |          |                   |
| I CS   | CEM I 52,5R | CS        |         | 207.5      | 4.0       |          |                   |
| I CN   | CEM I 52,5R | CN        |         | 211.5      | 3.0       |          |                   |
| II CF  | CEM II/B-S  | CF        |         | 202.5      | 5.0       |          |                   |
| II CS  | CEM II/B-S  | CS        |         | 207.5      | 4.0       |          |                   |
| II CN  | CEM II/B-S  | CN        |         | 211.5      | 3.0       |          |                   |
| III/A CF | CEM III/A | CF       |         | 202.5      | 5.0       |          |                   |
| III/A CS | CEM III/A | CS       |         | 207.5      | 4.0       |          |                   |
| III/A CN | CEM III/A | CN       |         | 211.5      | 3.0       |          |                   |
| III/C CF | CEM III/C | CF       |         | 202.5      | 5.0       |          |                   |
| III/C CS | CEM III/C | CS       |         | 207.5      | 4.0       |          |                   |
| III/C CN | CEM III/C | CN       |         | 211.5      | 3.0       |          |                   |

#### 2.3. Methods

Range of the report consists of results from initial setting time of cement and compressive strength of mortars tests. Specimens for both tests were prepared in $8 \pm 1^\circ C$ and $20 \pm 1^\circ C$. Mortar specimens for compressive strength made in temperature of $8 \pm 1^\circ C$ were cured in water until the test was conducted. Those prepared in temperature of $20 \pm 1^\circ C$ were cured in climatic chamber with relative humidity 60%.

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).

#### 3. Results and discussions

##### 3.1. Initial setting time

At first the initial setting time tests were conducted. Results are given in tables 3 and 4. All used accelerating admixtures cause decrease of initial setting time for all cement types examined in temperature $8^\circ C$ and $20^\circ C$. Effectiveness of crystal seeds (CS) and calcium nitrate (CN) based accelerators is similar in both temperatures. Effectiveness of calcium formate is lower in temperature $8^\circ C$.

For all types of cement, the most effective admixtures are those based on crystal seeds (CS) and calcium nitrate (CN). Those accelerators caused decrease of initial setting time by 30 – 40%. Their effectiveness is slightly greater in higher temperature (40 – 45%). Modification of mortars with calcium formate (CF) caused decrease of initial setting time by about 15 – 25% in temperature of $20^\circ C$ and by about 10 – 20% in temperature of $8^\circ C$. 
Table 3. Properties of mortars performed and cured in temperature 20°C

| Mortar symbol | Spreading diameter [cm] | Initial setting time [min] | Compressive strength [MPa] |
|---------------|------------------------|----------------------------|---------------------------|
|               |                        |                           | 12 hours  | 24 hours  | 48 hours  | 7 days  | 28 days |
| I             | 17.1                   | 160                       | 6.6       | 22.5      | 35.0      | 49.9     | 53.1     |
| II            | 20.5                   | 220                       | 2.9       | 10.4      | 17.9      | 26.8     | 30.0     |
| III/A         | 20.2                   | 252                       | 1.2       | 3.8       | 8.7       | 12.1     | 13.1     |
| III/C         | 20.5                   | 312                       | 0.0       | 0.5       | 1.1       | 4.0      | 4.2      |
| I CF          | 15.0                   | 110                       | 12.1      | 24.6      | 33.8      | 53.8     | 54.8     |
| I CS          | 21.7                   | 90                        | 12.8      | 25.6      | 35.1      | 56.3     | 57.4     |
| I CN          | 19.6                   | 93                        | 12.0      | 25.1      | 34.6      | 53.3     | 55.9     |
| II CF         | 18.3                   | 150                       | 4.8       | 11.4      | 18.3      | 40.6     | 42.5     |
| II CS         | 24.4                   | 130                       | 5.3       | 13.8      | 20.1      | 41.0     | 42.6     |
| II CN         | 21.2                   | 120                       | 6.0       | 13.9      | 21.4      | 40.0     | 42.9     |
| III/A CF      | 14.8                   | 198                       | 1.3       | 3.8       | 9.2       | 14.0     | 15.2     |
| III/A CS      | 21.3                   | 170                       | 1.5       | 4.4       | 9.3       | 16.1     | 18.1     |
| III/A CN      | 18.6                   | 183                       | 1.5       | 4.6       | 9.4       | 14.7     | 15.5     |
| III/C CF      | 16.0                   | 265                       | 0.0       | 0.5       | 1.0       | 5.3      | 5.6      |
| III/C CS      | 22.0                   | 213                       | 0.0       | 0.5       | 1.3       | 7.0      | 8.6      |
| III/C CN      | 18.0                   | 230                       | 0.0       | 0.5       | 1.3       | 5.7      | 6.3      |

Table 4. Properties of mortars performed and cured in temperature 8°C

| Mortar symbol | Spreading diameter [cm] | Initial setting time [min] | Compressive strength [MPa] |
|---------------|------------------------|----------------------------|---------------------------|
|               |                        |                           | 12 hours  | 24 hours  | 48 hours  | 7 days  | 28 days |
| I             | 20.1                   | 278                       | 2.6       | 9.0       | 13.8      | 38.5     | 57.5     |
| II            | 20.8                   | 400                       | 1.3       | 4.2       | 7.4       | 23.2     | 36.4     |
| III/A         | 20.7                   | 507                       | 0.0       | 0.0       | 4.0       | 11.9     | 25.9     |
| III/C         | 21.1                   | 728                       | 0.0       | 0.0       | 0.0       | 2.3      | 12.2     |
| I CF          | 18.8                   | 222                       | 8.5       | 16.3      | 22.2      | 47.8     | 62.8     |
| I CS          | 22.4                   | 163                       | 9.5       | 19.0      | 28.3      | 50.0     | 60.4     |
| I CN          | 20.0                   | 163                       | 6.2       | 15.2      | 19.8      | 45.4     | 57.0     |
| II CF         | 15.7                   | 277                       | 2.8       | 7.4       | 11.6      | 31.5     | 51.0     |
| II CS         | 20.3                   | 238                       | 3.7       | 9.9       | 14.1      | 31.3     | 46.4     |
| II CN         | 19.8                   | 215                       | 2.8       | 7.3       | 10.4      | 28.7     | 47.1     |
| III/A CF      | 14.0                   | 423                       | 0.4       | 2.0       | 4.0       | 12.5     | 34.6     |
| III/A CS      | 20.7                   | 340                       | 0.5       | 2.5       | 5.4       | 14.1     | 33.9     |
| III/A CN      | 18.1                   | 363                       | 0.4       | 1.5       | 3.6       | 12.7     | 30.8     |
| III/C CF      | 14.8                   | 672                       | 0.0       | 0.0       | 0.0       | 1.8      | 17.8     |
| III/C CS      | 18.0                   | 505                       | 0.0       | 0.0       | 0.0       | 3.8      | 16.0     |
| III/C CN      | 16.7                   | 540                       | 0.0       | 0.0       | 0.0       | 3.6      | 19.3     |

3.1. Spread diameter
Flow table test was second of conducted examinations. Spread diameter of non-modified mortars and ones containing admixtures based on calcium nitrate (CN) and calcium formate (CF) after demoulding is similar and equal to 10.0 – 10.5 cm. Spread diameter of mortars modified with admixture based on crystal seeds is greater by 1.0 – 3.0 cm, depending on cement type.
Final spread diameters of mortars in temperature 20°C are shown in table 3. In the case of non-modified mortars, the spread diameter of those with GGBFS is larger than of Portland cement based one. Differences between cements with various GGBFS quantity is not significant. Admixtures with calcium nitrate (CN) and crystal seeds (CS) cause increase of CEM I 52,5R and CEM II/B-S mortars’ spread diameter in comparison to reference mortars. More significant enhancement occurs in case of crystal seeds based admixture (CS). In case of CEM III/A,B mortars spread diameter is visible only for the latter. Calcium formate (CF) in all cases decrease final spread diameter of mortars. In temperature of 8°C spread diameters are generally greater but differences between cement types are not as strong as in 20°C (table 4).

3.2. Compressive strength

Compressive strength tests’ results conducted for specimens cured in 20°C is shown in table 3. Results of those cured in 8°C is shown in table 4. Non-modified mortars containing cements with larger amount of GGBFS have lower compressive strength in terms 12 hours to 28 days, independently of curing temperature. In temperature of 20°C mortars containing cement with 95% of GGBFS (CEM III/C) attained enough compressive strength to perform the test after 24 hours. In temperature of 8°C mortars made with cement with 65% GGBFS (CEM III/A) have not obtained strength required to perform the test after 12 and 24 hours. Those containing cement with 95% of GGBFS (CEM III/C) after 48 hours as well.

After 12 hours of curing in 20°C mortars created with Portland cement (CEM I 52,5R) and Portland slag cement (CEM II/B-S) modified with accelerators gained compressive strength greater by about 40% in comparison to non-modified ones. In case of mortars made with blast furnace cement (CEM III/A) there is no increase of compressive strength. Modified mortars containing cement with 95% of GGBFS (CEM III/C) did not gain required compressive strength to perform examination.

All admixtures caused increase of compressive strength after 24 hours of curing in case of mortars made with cements CEM I 52,5R and CEM II/B-S. This is lower enhancement than in previous term. Accelerators have similar efficiency for Portland cement. For Portland slag cement the most efficient is calcium nitrate (CN) and the worst is calcium formate (CF). Blast furnace cement with 65% of GGBFS (CEM III/A) gained greater compressive strength after modification with calcium nitrate (CN) and crystal seeds (CS) by about 15% in comparison to reference sample. Calcium formate (CF) did not influenced the compressive strength. Both modified and non-modified mortars made with blast furnace cement with 95% of GGBFS (CEM III/C) had similar compressive strength.

After 48 hours the only cement for which influence of calcium nitrate (CN) and crystal seeds (CS) is significant is CEM II/B-S. Enhancement is by about 10 – 15%. Calcium formate did not changed compressive strength. For CEM I 52,5R and both CEM III/A,C influence of all accelerators is low.

All admixtures increased compressive strength after 7 and 28 days. The biggest profits are in case of CEM III/C – about 40% caused by calcium nitrate (CN) and calcium formate (CF) and up to 100% caused by crystal seeds (CS). For Portland cement (CEM I 52,5R) this increase is 5 – 10%, for Portland-slag cement (CEM II/B-S) 25 – 30% and for blast furnace cement (CEM III/A) 20 – 30%.

In lower temperature (8°C) relations are similar. Although results obtained in both temperatures cannot be compared because of different humidity during curing. After 12 hours of curing in 8°C the most efficient accelerators for Portland cement (CEM I 52,5R) are crystal seeds (CS) and calcium formate (CN). They improve compressive strength by 3 – 4 times. For Portland-slag cement (CEM II/B-S) crystal seeds (CS) based admixture is also the most efficient. It improves compressive strength by 300%. Calcium nitrate (CN and calcium formate (CF) improve it by 2 times. Modified blast furnace cement (CEM III/A) gain minimal required compressive strength for examination. Blast furnace cement with larger amount of GGBFS (95%) did not gain such strength up to 48 hours.

24 and 48 hours’ compressive strength of mortars made with Portland cement (CEM I 52,5R) and Portland-slag cement (CEM II/B-S) is greater by 70 – 120% dependently on admixture type. The most efficient is crystal seeds (CS) based one. Modified CEM III/A gains similar compressive strength with all accelerators. Non-modified one did not gain such strength after 24 hours.
After 7 days curing time beneficial influence of accelerators on Portland cement and Portland slag cement compressive strength is lower (10 – 30%). There is no significant improvement in case of both blast furnace cements.

After 28 days’ influence of accelerators on Portland cement is minimal. Compressive strength of modified mortars made of cements with GGBFS is significantly higher than non-modified ones.

3.3. Multi-criteria decision analysis

For determination of effectiveness relations, the multi-criteria decision analyses (MCDA) were performed. Because of different behaviour of examined types of cement, analyses were conducted for each one separately. 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 of analysis is to determine its aim. As mentioned it is to compare effectiveness of accelerating admixtures for concrete in terms of initial setting time shortening and compressive strength or mortars increase simultaneously. The second step is to create list of criteria according to which admixtures action is to be graded. Criterion of initial setting time was divided according to temperature of examination. Because it is better to obtain shorter initial setting time those criteria are dampers. Criterion of compressive strength was divided according to temperature and humidity while curing. Because it is better to obtain greater compressive strength in each term and enhanced workability those criteria are boosters. Final set of criteria is given in table 5.

### Table 5. Accelerating admixtures characteristics

| Symbol | Criteria | Type of criterion |
|--------|----------|-------------------|
| K1     | Initial setting time in temperature of 20°C | Damper |
| K2     | Initial setting time in temperature of 8°C | Damper |
| K3     | Spread diameter | Booster |
| K4     | Compressive strength of mortars cured in temperature of 20°C after 12 hours | Booster |
| K5     | Compressive strength of mortars cured in temperature of 20°C after 24 hours | Booster |
| K6     | Compressive strength of mortars cured in temperature of 20°C after 48 hours | Booster |
| K7     | Compressive strength of mortars cured in temperature of 20°C after 7 days | Booster |
| K8     | Compressive strength of mortars cured in temperature of 20°C after 28 days | Booster |
| K9     | Compressive strength of mortars cured in temperature of 8°C after 12 hours | Booster |
| K10    | Compressive strength of mortars cured in temperature of 8°C after 24 hours | Booster |
| K11    | Compressive strength of mortars cured in temperature of 8°C after 48 hours | Booster |
| K12    | Compressive strength of mortars cured in temperature of 8°C after 7 days | Booster |
| K13    | Compressive strength of mortars cured in temperature of 8°C after 28 days | Booster |

The third step of MCDA is determination of criteria weights. It was done with usage of pair analysis. It is conducted by preforming of the $n \times n$ matrix, where $n$ denotes number of criteria. Then the sum in each row is calculated and is divided by number of criteria ($n$). Values of elements in this matrix are calculated by formula (1).

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

(1)
Resultant matrix of criteria’s weights, sum of rows and sum of rows divided by number of criteria \( (n) \) is as follows:

\[
M_g = \begin{bmatrix}
0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
11
\end{bmatrix} = 0.79
\]

The ultimate step is analysis and ordering of the results. Detailed calculations are given in tables 6 – 9. In case of all cement types the admixture based on crystal seeds (CS) is the best solution according to chosen criteria and their weights. The second one is the one with calcium nitrate (CN). The lowest results were obtained for calcium formate (CF) based admixture.

| Table 6. Mean and coded values and resultant for CEM I 52,5R |
|---------------------------------|
| Admixtures’ symbol | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 | K9 | K10 | K11 | K12 | K13 | Sum  |
| Mean values         | CF | 110| 222| 15.0| 12.1| 24.6| 33.8| 53.8| 54.8| 8.5 | 16.3| 22.2| 47.8| 62.8 |
|                    | CS | 90 | 163| 21.7| 12.8| 25.6| 35.1| 56.3| 57.4| 9.5 | 19.0| 28.3| 50.0| 60.4 |
|                    | CN | 93 | 163| 19.6| 12.0| 25.1| 34.6| 53.3| 55.9| 6.2 | 15.2| 19.8| 45.4| 57.0 |
| Weight of criteria  | CF | 0.79| 0.79| 0.00| 0.64| 0.50| 0.07| 0.07| 0.36| 0.64| 0.50| 0.07| 0.07| 0.36 |
|                    | CS | 0.00| 0.00| 0.00| 0.12| 0.00| 0.00| 0.17| 0.00| 0.70| 0.29| 0.28| 0.52| 1.00 |
|                    | CN | 0.85| 1.00| 0.69| 0.00| 0.50| 0.62| 0.00| 0.42| 0.00| 0.00| 0.00| 0.00| 0.00 |
| Coded values       | CF | 0.00| 0.00| 0.00| 0.08| 0.00| 0.00| 0.01| 0.00| 0.45| 0.14| 0.02| 0.04| 0.36 |
|                    | CS | 0.79| 0.79| 0.00| 0.64| 0.50| 0.07| 0.07| 0.36| 0.64| 0.50| 0.07| 0.07| 0.21 |
|                    | CN | 0.67| 0.79| 0.00| 0.25| 0.04| 0.00| 0.15| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00 |
| Resultant          | CF | 0.00| 0.00| 0.00| 0.08| 0.00| 0.00| 0.01| 0.00| 0.45| 0.14| 0.02| 0.04| 0.36 |
|                    | CS | 0.79| 0.79| 0.00| 0.64| 0.50| 0.07| 0.07| 0.36| 0.64| 0.50| 0.07| 0.07| 0.21 |
|                    | CN | 0.67| 0.79| 0.00| 0.25| 0.04| 0.00| 0.15| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00 |
Table 7. Mean and coded values and resultant for CEM II/B-S

| Criteria | K1   | K2   | K3   | K4   | K5   | K6   | K7   | K8   | K9   | K10  | K11  | K12  | K13  |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Mean     | CF   | 150  | 277  | 18.3 | 4.8  | 11.4 | 18.3 | 40.6 | 42.5 | 2.8  | 7.4  | 11.6 | 31.5 | 51.0 |
|          | CS   | 130  | 238  | 24.4 | 5.3  | 13.8 | 20.1 | 41.0 | 46.2 | 3.7  | 9.9  | 14.1 | 31.3 | 46.4 |
|          | CN   | 120  | 125  | 21.3 | 6.0  | 13.9 | 21.4 | 40.0 | 42.9 | 2.8  | 7.3  | 10.4 | 28.7 | 47.1 |
| Weight of | CF   | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|          | CS   | 1.00 | 1.00 | 0.49 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.15 |
| Coded    | CF   | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.51 |
|          | CS   | 0.52 | 0.20 | 0.00 | 0.27 | 0.48 | 0.04 | 0.36 | 0.64 | 0.50 | 0.07 | 0.07 | 0.00 | 2.22 |
| Resultant| CF   | 0.79 | 0.79 | 0.64 | 0.50 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.88 |

Table 8. Mean and coded values and resultant for CEM III/A

| Criteria | K1   | K2   | K3   | K4   | K5   | K6   | K7   | K8   | K9   | K10  | K11  | K12  | K13  |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Mean     | CF   | 198  | 423  | 14.8 | 1.3  | 3.8  | 9.2  | 14.0 | 15.2 | 0.4  | 2.0  | 4.0  | 12.5 | 34.6 |
|          | CS   | 170  | 340  | 21.3 | 1.5  | 4.4  | 9.3  | 16.1 | 18.1 | 0.5  | 2.5  | 5.4  | 14.1 | 33.9 |
|          | CN   | 183  | 363  | 18.6 | 1.5  | 4.6  | 9.4  | 14.7 | 15.5 | 0.4  | 1.5  | 3.6  | 12.7 | 30.8 |
| Weight of | CF   | 0.79 | 0.79 | 0.64 | 0.50 | 0.07 | 0.07 | 0.36 | 0.64 | 0.50 | 0.07 | 0.07 | 0.00 | 3.29 |
|          | CS   | 1.00 | 1.00 | 1.00 | 0.75 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 4.63 |
| Coded    | CF   | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 0.36 |
|          | CS   | 1.00 | 1.00 | 1.00 | 0.75 | 0.50 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 4.63 |
| Resultant| CF   | 0.79 | 0.79 | 0.64 | 0.38 | 0.04 | 0.07 | 0.36 | 0.64 | 0.50 | 0.07 | 0.07 | 0.29 | 2.27 |

Table 9. Mean and coded values and resultant for CEM III/C

| Criteria | K1   | K2   | K3   | K4   | K5   | K6   | K7   | K8   | K9   | K10  | K11  | K12  | K13  |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Mean     | CF   | 265  | 672  | 16.0 | 0.0  | 0.5  | 1.0  | 5.3  | 5.6  | 0.0  | 0.0  | 1.8  | 17.8 |
|          | CS   | 213  | 505  | 22.0 | 0.0  | 0.5  | 1.3  | 7.0  | 8.6  | 0.0  | 0.0  | 3.8  | 16.0 |
|          | CN   | 230  | 540  | 18.0 | 0.0  | 0.5  | 1.3  | 5.7  | 6.3  | 0.0  | 0.0  | 3.6  | 19.3 |
| Weight of | CF   | 0.79 | 0.79 | 0.64 | 0.50 | 0.07 | 0.07 | 0.36 | 0.64 | 0.50 | 0.07 | 0.07 | 0.00 |
|          | CS   | 0.67 | 0.79 | 0.33 | 0.00 | 1.00 | 1.00 | 0.24 | 0.23 | 0.00 | 0.00 | 0.90 | 1.00 |
| Coded    | CF   | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.55 |
|          | CS   | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| Resultant| CF   | 0.79 | 0.79 | 0.64 | 0.50 | 0.07 | 0.07 | 0.36 | 0.64 | 0.50 | 0.07 | 0.07 | 0.00 |
|          | CS   | 0.53 | 0.62 | 0.00 | 0.00 | 0.50 | 0.07 | 0.02 | 0.08 | 0.00 | 0.00 | 0.00 | 0.36 |
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). The difference between them is not significant. Calcium formate (CF) 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 slightly. It is not possible to determine which accelerator is the most efficient in compressive strength enhancement.

- None of examined set and hardening accelerating admixtures has caused decrease of compressive strength after 28 days.

- 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. The second is the one with calcium nitrate (CN). The lowest results were obtained for calcium formate (CF) based admixture.

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