Development and Optimization of High Early Strength Concrete Mix Design

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Abstract. The paper presents the results of tests of compressive strength, heat of hardening and crack resistance of high-performance concretes, which composition was chosen to ensure high early strength. This enables the proper rotation of moulds in prefabrication plants, without the thermal treatment. It has been proven that achieving a compressive strength of 36 MPa after 16 hours is possible by using CEM I 52.5 R Portland cement. In this case the temperature rises slightly during the concrete hardening in comparison to concrete with CEM II/A-S 52.5N slag cement, what can lead to higher thermal stresses in the element. On the other hand, the use of Portland cement reduces the risk of cracking caused by shrinkage, what is shown by smaller values of stress rate q.

1. Introduction
During the production of precast elements, it is desirable to use concretes with the highest possible early strength, as it enables to obtain a number of benefits such as:

- Rapid rotation of moulds and finishing of concrete surfaces
- Reduced cycle times that allow the reduction of the number of moulds required
- Early pre-stressing even at lower temperatures (precast production is often conducted in poorly heated halls)
- Reduced energy consumption for heat or steam curing, or even eliminating the necessity of heat or steam curing.

In the production of prestressed precast elements, the element is demoulded after releasing the string tension. Due to the need to bear large prestressing forces, it is required that the class of concrete is at least C30/37 at the moment of tension release, what corresponds to the compressive strength of concrete at the level of 36 MPa. Due to maximal economic effects, it is required that this strength is obtained as soon as possible, preferably in a time not exceeding 16 hours, which allows the production of elements in a one-day cycle. Obtaining such a high early strength, especially without the use of thermal treatment, requires a special approach to designing the composition of the concrete mix. The mixture should be characterized by a relatively large amount of cement with high early strength, low w/c ratio and good workability, which is obtained using a properly selected superplasticizer. It should also be noted that in addition to the requirement of high early strength, the issue of adequate durability of concrete is very important. Thermal effects resulting from the use of a large amount of cement of high early strength can lead to the thermal strains. In worst case scenario, this can lead to cracking and loss of durability [1-3]. For technical reasons, it is therefore beneficial to aim for cement content in concrete to be as low as possible. At the same time, minimizing the amount of cement in concrete is vital for both economic and ecological reasons [4].
The aim of the research presented in the paper was to obtain cost-efficient concrete intended for the production of prestressed concrete elements. This concrete should be characterized by early strength exceeding 36 MPa after 16 hours of curing without thermal treatment. Cost-effectiveness was achieved by optimizing the composition of concrete by the minimization of the amount of cement.

2. Plan and methodology of research
The aim of the research was to determine the impact of the w/c ratio and the amount of cement on early concrete strength, and on this basis to obtain and optimize the composition of concrete derived from the condition of compressive strength after 16 hours greater than 36 MPa. The concrete compressive strength of 28 days should correspond to class C50/60 and therefore reach at least 56 MPa. The composition of the concrete was optimized for the minimization of the amount of cement. In addition to the compressive strength, thermal effects and crack resistance of the concrete were also tested.

As the reference, the concrete used in the actual production of prestressed concrete elements (concrete B0, shown in table 1) was assumed. It was assumed that the consistency of the concrete mix measured by the slump should be about 160 - 190 mm, which corresponds to the consistency class S4. The research was divided into stages (figure 1). In the first stage, CEM I 52.5 R Portland cement was introduced instead of the CEM II A/S cement, while changing its amount and the w/c ratio (B1 - B3 shown in table 1, assumed consistency was obtained by adding the appropriate amount of superplasticizer). In the second stage, after verifying the strength after 16h, the amount of cement in the concrete was reduced by w/c = 0.37 (Concrete B4 and B5 according to table 1). In the last stage, a concrete B6 with the amount of cement equal to 440 kg/m³ and w/c = 0.37 was obtained, the composition of which was assumed in such a way that the amount of mortar was equal to the amount of mortar in B3 mix with cement content equal to 480 kg/m³. This allowed reducing the risk of surface defects caused by the so-called “wall effect”.

![Figure 1](image_url)

**Figure 1.** Research plan and designation of concretes used in the research.

Properties of CEM II A-S 52.5 R and CEM I 52.5 R cements are shown in table 1. Basalt fractions 2-8 and 8-16 mm as well as normal sand of 0-2 mm were used as aggregate. The aggregate grading is shown in figure 2. The proportions of aggregates in B0-B5 have been constant and the aggregate grading curve was the same for each concrete. The total amount of aggregate changed, which was
dictated by the variable content of cement and the w/c ratio. The aggregate grading curve for B6 mix is characterized by a larger sand amount (31% compared to 28.3%), due to the above-mentioned assumption of an equal amount of mortar in B3 and B6 concretes. To obtain the assumed consistency, superplasticizer based on sulphated naphthalene and melamine polycondensates was used. Compositions of concretes B0 – B6 are shown in table 2.

**Table 1. Properties of cement.**

| Cement          | Density [g/cm³] | Water demand [%] | SO₃ [%] | LOI [%] | Time of setting [min] | Compressive strength [MPa] | Compressive strength [MPa] | Specific surface area [cm²/g] |
|-----------------|----------------|------------------|--------|---------|------------------------|----------------------------|----------------------------|-------------------------------|
| CEM I 52.5 R    | 3.10           | 32.8             | 2.20   | 1.08    | 174                    | -                          | 38.5                       | 68.9                          | 4973                          |
| CEM II/ A-S 52.5 N | 3.04           | 30.6             | 3.15   |         | 241                    | -                          | 28.3                       | 62.7                          | 4169                          |

**Figure 2. Aggregate grading curves of aggregate for concrete mixes B0-B6.**

For the concretes B0-B6, following tests were performed:

- Consistency of concrete mix (according to EN 12350-2 [5])
- Density of concrete mix
- Air-content of the concrete mix (according to EN 1015-7 [6])
- Compressive strength of concrete after 16 h, 7 and 28 days (according to EN 12390-3 [7])
- Development of concrete hardening temperature – measurements were performed on cubic samples 250 mm on a side insulated using styrofoam coating of thickness 100 mm and thermal conduction coefficient 0.044 W/m·K (figure 3). Temperature measurement was performed in the middle of cube. External temperature during the measurement was 20°C.
- Crack resistance according to ASTM C1581-04 [8].
Figure 3. Sample of fresh concrete with thermal insulations and Vikasonic system for temperature measurement, prepared to measure.

The tests were conducted in temperature 20 °C. Samples for compressive strength tests after 7 and 28 days matured in moulds covered with PE foil for 24 hours and then were stored in water at 18 °C.

The tests of consistency, air content or the compressive strength do not require in-depth description. The measurement of heat of hardening is also quite simple and its methodology well known. However, the procedure of testing crack resistance according to ASTM C1581-04 [9] may require a detailed description. The test consists of measuring the stresses that are exerted on the steel ring by hardening concrete. The test should be carried out until the 28th day of hardening or until the concrete ring cracks, what is indicated by a sharp reduction in the deformation of the steel ring. In the presented studies, the test duration was limited to 7 days, the samples were stored in a climate chamber, maintaining relative humidity of 60% and a temperature of 20° C. The assessment of susceptibility to cracking of the concretes was made by calculating the stress rate $q$ at the time of stopping of the test i.e. on day 7. Stress rate $q$ is calculated using the formula:

$$q = \frac{G|\varepsilon|}{2\sqrt{t}}$$

where: $q$-stress rate of test specimen (MPa/Day); $G$-Young modulus of inner steel ring $G=72.2$ GPa; $\varepsilon$-strain rate factor mm/day$^{1/2}$; $t$-elapsed time when the test was terminated, days.

Strain rate factor is the slope of the line, which is used to approximate the dependency between the deformation of the ring and a square root of the duration of the test.

3. Plan and methodology of research

Table 2 shows the compositions of concrete mixes with the results of tests on the density of mixtures, the air content $A_c$ and the consistency measured by the slump test. Concrete mix compositions were calculated based on the density of the mixes. The results of tests of compressive strength, temperature of hardening and stress rate $q$ are shown in table 3.

For all mixes, consistency S4 was assumed.

The mixtures are characterized by the amount of air at the level of 1%. Superplasticizer used in the research was not exhibiting any air-entraining behaviour.
Table 2. Composition and properties of concrete mixes used in the research

| Constituent /property | B0  | B1  | B2  | B3  | B4  | B5  | B6  |
|-----------------------|-----|-----|-----|-----|-----|-----|-----|
| Assumed amount of cement kg | 480 | 440 | 460 | 480 | 460 | 440 | 440 |
| CEM I 52.5 R kg | 438 | 460 | 476 | 457 | 437 | 438 |
| CEM II/A-S 52.5 N kg | 477 | | | | | |
| Water kg | 176 | 145 | 161 | 177 | 169 | 162 | 162 |
| W/C | 0.37 | 0.33 | 0.35 | 0.37 | 0.37 | 0.37 | 0.37 |
| Superplasticizer % | 1.2 | 1.60 | 1.4 | 1.2 | 1.2 | 1.2 | 1.50 |
| Superplasticizer kg | 5.69 | 7.00 | 6.42 | 5.68 | 5.48 | 5.28 | 6.55 |
| Sand 0-2 kg | 524 | 560 | 547 | 524 | 535 | 548 | 601 |
| Basalt 2-8 kg | 692 | 740 | 721 | 692 | 707 | 725 | 694 |
| Basalt 8-16 kg | 673 | 719 | 678 | 672 | 687 | 702 | 673 |
| Volume of the mortar Vz dm³ | 533 | 504 | 522 | 533 | 523 | 514 | 536 |
| Density of the mix ρmb kg/m³ | 2548 | 2609 | 2574 | 2547 | 2560 | 2579 | 2575 |
| Air content Ac % | 1.2 | 1.0 | 1.2 | 1.2 | 1.2 | 1.0 | 0.8 |
| Slump mm | 180 | 180 | 175 | 190 | 190 | 170 | 150 |

Table 3. Concretes B0-B6 properties

| Constituent /property | B0  | B1  | B2  | B3  | B4  | B5  | B6  |
|-----------------------|-----|-----|-----|-----|-----|-----|-----|
| Compressive strength [MPa] | | | | | | | |
| After 16 h | 33.7 | 52.6 | 49.6 | 44.5 | 42.4 | 43.3 | 45.2 |
| After 7 days | 60.9 | 82.9 | 83.6 | 79.2 | 79.9 | 81.2 | 81.9 |
| After 28 days | 84.1 | 104.6 | 95.6 | 91.3 | 91.2 | 94.4 | 91.3 |
| Concrete class | | | | | | | |
| After 16 h | C20/25 | C35/45 | C35/45 | C30/37 | C30/37 | C30/37 | C30/37 |
| After 7 days | C45/55 | C60/75 | C60/75 | C60/75 | C60/75 | C60/75 | C60/75 |
| After 28 days | C60/75 | C80/95 | C70/85 | C70/85 | C70/85 | C70/85 | C70/85 |
| Maximal temperature [°C] | 63.0 | 70.3 | 77.9 | 79.0 | 73.2 | 70.0 | 71.3 |
| Time of maximal temperature [hh:min] | 19:28 | 17:14 | 16:18 | 17:54 | 16:02 | 17:43 | 17:12 |
| Steel ring strain after 7 days | 77.08 | 71.86 | 63.75 | 62.71 | 56.15 | 57.08 | 59.16 |
| Stress rate q [MPa/Day] | 0.54 | 0.37 | 0.33 | 0.34 | 0.32 | 0.30 | 0.36 |

All of the tested concretes with cement CEM I exhibit higher strength class than set C50/60, even after 7 days, and after 28 days the concretes reach strength class C70/80 or higher.

4. Results and discussion

Exchanging the CEM II/A-S cement with CEM I 52.5 R cement without a correction of other parameters of the composition (B3) allows obtaining the compressive strength of 44.5 MPa after 16 hours, what exceeds the set strength requirement by 24%. Lowering the w/c ratio significantly raises the compressive strength, in case of concretes B1 and B2; this allowed reaching the set early compressive strength with a large margin of respectively 46% and 38%. In concretes B4, B5 and B6...

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with w/c=0.37 the amount of cement was lowered to 440 kg/m³ what allowed to obtain the compressive strength after 16h at the level of 42 – 45 MPa, which is over 20% higher than required strength. It should be noted, that reduction of the amount of cement does not significantly affect the early compressive strength. Taking under consideration the amount of cement and how much cement must be used for 1 MPa of compressive strength of concrete after 16h of hardening (figure 4) the most beneficial composition is B6.

![Figure 4. Compressive strength of concretes after 16h, 7 and 28 days](image)

The difference between concretes B5 and B6, which differ by the amount of sand in the concrete mix, is interesting. After 16h of hardening, the compressive strength of B6 (which has less sand and thus more mortar) is higher than of B5. However, after 28 days the situation is other way round, as the concrete B5, which has less mortar reaches higher compressive strength.

![Figure 5. The amount of cement needed to obtain 1 MPa of compressive strength](image)
The compressive strength of concrete depends on many factors, such as the strength of constituents, but also the bonds and forces between the constituents, for example adhesion between the surface of the coarse aggregate and mortar, and between aggregate and cement paste. Initially, the forces of adhesion between coarse aggregate and mortar are not strong, meaning that the contact zone between them is the weakest spot in the concrete [9]. Thus, in the initial hardening stages the mortar plays the bigger part in the strength of concrete than the aggregate, what means that the concrete with higher amount of mortar has a higher early compressive strength than concrete with a lower content of mortar. After 28 days, when the contact zone becomes tighter and thus the forces of adhesion increase and the loads are mostly borne by basalt aggregate.

Temperature of hardening is higher for concretes with Portland cement (figure 6).

The maximal temperature of concrete B3 with Portland cement is higher by 15 °C than concrete B0 with Portland slag cement. Decreasing the amount of cement allows decreasing the amount of heat released during the hardening of concrete. Obtaining the compressive strength after 16 h at a set level is dependent on the conditions of concrete curing. If the temperature of curing is lower than 20 °C it might be beneficial to use concrete with lower w/c ratio or higher content of cement due to the higher temperatures of concrete during the hardening.

![Figure 6. Maximal temperature of concrete during hardening](image)

In case of concrete with low w/c ratio and relatively high content of cement, the issue of crack resistance is particularly important [10]. Shrinkage effects in concrete during initial stages of hardening are particularly dynamic. While it can be argued that the shrinkage strain can be borne by the concrete due to its high tensile strength, the modulus of elasticity is also rapidly increasing during the hardening of concrete, what can cause the shrinkage strain to exceed the tensile stress. This situation leads to cracking of the concrete, and this causes lowering of compressive strength of concrete. The deformation of a steel ring caused by a shrinkage of a concrete ring is shown in figure 7. During the first 7 days, no cracks were detected. The decrease in deformation of steel ring during the first 24 h is most probably caused by the observed increase of temperature in concrete. The shrinkage of concrete ring was then reduced, due to the thermal expansion of the ring. Based on the obtained steel ring strain, stress rate \( q \) was calculated, what was the basis for evaluation of the susceptibility to cracking (figure 8).
The coefficient of the increase in the load exerted by the concrete on the steel ring (stress rate q) is the highest for concrete B0, which is the concrete with the largest amount of cement paste. The higher amount of cement paste causes higher shrinkage, and thus the strain in the ring is higher and takes place earlier. Replacing the CEM II/A-S 52.5 cement (concrete B0) with CEM I 52.5 R (B3) it is possible to significantly lower the stress rate q. Concretes have the same amount of cement paste, so this effect should be attributed to the properties of cements. The lower specific surface of Portland composite cement and disadvantageous shape of the cement grains (due to the presence of ground granulated blast furnace slag) can cause a higher amount of capillary pores. The moisture movement in capillary pores causes the shrinkage, thus the stress rate q for concrete B0 with CEM II A-S 52.5 is significantly higher. Stress rates q of concretes with Portland cement are similar, with the value around 0.34 MPa/day. According to ASTM C 1581-04 they can be considered to have a high or moderate-
high potential for cracking. Taking under consideration the potential for cracking, the best is concrete B5, which stress rate \( q \) is 0.30 MPa/day and is the lowest among tested cements.

5. Conclusions

Obtaining the early compressive strength of 36 MPa without the thermal treatment is possible. Concretes B1 – B6 (composition shown in Table 1) are characterized by consistency class S4 and compressive strength after 16 h higher by at least 20% than set 36 MPa.

Early compressive strength of concrete is dependent on the w/c ratio; lowering the amount of cement (in the research in the range of 280 – 440 kg/m\(^3\)) does not significantly affect the early compressive strength. This allows using lower amounts of cement and in turn lowering the self-heating of the elements and increasing their resistance to cracking caused by thermal deformation. Using cement CEM I 52.5 R causes an increase in heat released during hardening and increases the possibility of thermal strain in formed elements (especially during the demoulding and/or during winter). This issue should be a subject of further research.

In the tested concretes, no cracking was detected during the first 7 days of hardening; however, the potential for cracking was high. Using Portland cement CEM I 52.5 R as a replacement for CEM II/A-S 52.5 allows to reduce the risk of shrinkage cracking. Decrease of the amount of cement allows furthering reducing the risk.

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