Low heat concrete with ground granulated blast furnace slag

Yu Barabanshchikov¹, K Usanova¹, S Akimov¹ and P Bíly²
¹ Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Russian Federation
² Czech Technical University, Prague, Czech Republic

plml@mail.ru

Abstract. The subject of the research is a concrete with partial replacement of cement with an increased amount of ground granulated blast furnace slag to reduce heat release of concrete for the structures of the Akkuyu Nuclear Power Plant (İskenderun, Turkey). The concrete was tested for heat release, compressive strength and shrinkage. Several mixes with partial replacement of cement by the slag from «İskenderun Demir ve Çelik A.Ş.» were used for testing. The heat release is reduced by up to 50 % and the loss of strength is not more than 36 %. This is the result of an increase in the slag content in the mixed binder (cement + slag) and a decrease in the cement content. The optimal slag content in the mixed binder is 25 %.

There is an increase in concrete strength by 3-4 % and a decrease in heat release by 13 % compared to the cement binder. All tested concrete mixtures with the cement replacement by the slag have a decrease of the heat release, which is greater than a decrease in the concrete strength. The cement replacement by the slag leads to an increase in autogenous shrinkage. If the binder contains 50 % of the slag, the highest value of the autogenous shrinkage is observed. This value is approximately twice greater than the shrinkage of concrete with the cement binder. If the binder contains 75 % of the slag, the shrinkage is less. The replacement of the cement content by the slag is recommended to reduce the heat release of concrete, in order to increase its thermal crack resistance.

1. Introduction

The cement industry has a significant impact on the situation in the global environment. The production of cement is a major source of greenhouse gas emissions [1]. Cement for concrete can be partially replaced by different supplementary cementitious materials [2-5]. It is a promising method for reducing the environmental impact from the industry.

The most commonly used cement replacement material is ground granulated blast furnace slag, which is a by-product from the blast furnaces in the iron-making industry [6]. The use of this material gives significant economic and resource-saving effects [7, 8].

The ground granulated blast furnace slag is well studied as an active mineral admixture in cements [9-12]. Moreover, blast-furnace slag is the main component in the production of slag cement [13-16]. Other admixtures for lightweight concrete are known: diatomite, silica fume, granite, perlite, vermiculite etc. The properties of these admixtures are studied in the works [17-19]. They are also used in lightweight steel concrete structures [20, 21].
It is well known, that one of the important properties of cement is its heat release, which affects the quality of concrete works, construction timelines and durability of concrete structures [22]. Cracks appear in hardening concrete because of the heat of hydration of cement. These cracks are caused by uneven and moderate temperature deformations [23-25].

There are different technical solutions for controlling the thermal conditions of hardening concrete and reducing temperature differences [26-29]. The most significant measure to ensure thermal crack resistance of concrete is reducing its heat release. This could be achieved by reducing the cement content in the mix and the use of low heat cements.

The heat release of concrete is usually less in case if the cement and the admixtures for concrete (ground granulated blast furnace slag, fly ash, silica fume, etc.) are used together [30]. But reducing weight of cement in the mix leads to a strength reduction of concrete and affects the workability of the mixture [31, 32]. A study [33] determined that the optimal content of ground granulated blast furnace slag is 30% in the case of the partial replacement of cement. In that way, the strength decreases on average by 11% and a reduction of CO$_2$ emissions by 30%.

A study [34] shows that the total heat of hydration in isothermal conditions decreases in the case of the increase in the proportion of ground granulated blast furnace slag as a binder. The degree of hydration of that cement and amount of reacted slag increase with temperature. They decrease with a greater proportion of cement replacement by slag [35, 36].

The subject of our research is concrete with partial replacement of cement with an increased amount of ground granulated blast furnace slag produced by «İskenderun Demir ve Çelik A.Ş.» (İskenderun, Turkey).

The objectives of the work are experimental studies of concrete with partial replacement of cement with ground granulated blast furnace slag, determination of hydration kinetics and possibilities for reducing heat release of concrete for the structures of the Akkuyu Nuclear Power Plant (İskenderun, Turkey).

2. Materials and methods
The slag content was tested in Peter the Great St. Petersburg Polytechnic University (Russia).

Concrete mixture consisted of:
1. Portland cement CEM I 42.5 N produced by Medcem Madencilik ve Yapı Malzemesi San. Tic. A.S (Turkey). Standard consistence is 24.6%, standard strength is 48.8 MPa, early strength at the age of 2 days is 18.6 MPa, initial setting time is 270 min. Chemical composition and mineralogical composition of the cement are presented in Table 1 and Table 2.

| Table 1. Chemical composition of the cement [%]. |
|-----------------------------------------------|
| SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | K$_2$O | Na$_2$O |
| 20.35 | 4.10 | 4.47 | 61.47 | 1.53 | 2.69 | 0.70 | 0.12 |

| Table 2. Mineralogical composition of the cement [%]. |
|-----------------------------------------------|
| C$_3$S | C$_2$S | C$_3$A | C$_4$AF |
| 53.88 | 17.6 | 3.3 | 13.6 |

2. Fine aggregate, which consists of a mixture of sand and limestone crushing screenings. The sand has fineness modulus of 1.7 and grain size of 0-1 mm. The limestone crushing screenings have fineness modulus of 3.1 and grain size of 0-4 mm.

3. Crushed trap rock, which has grain size of 4-11 mm and 11-22 mm.

4. Ground granulated blast furnace slag produced by Adana Çimento Sanayii TAŞ (Turkey). True density is 2920 kg/m$^3$ and specific surface area is 5190 cm$^2$/g. Chemical composition of the ground granulated blast furnace slag is presented in Table 3.
Table 3. Chemical composition of the ground granulated blast furnace slag [%].

|                | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO  | MgO  | SO$_3$ | loss on ignition |
|----------------|---------|-------------|-------------|------|------|--------|------------------|
|                | 37.96   | 11.09       | 0.75        | 38.41| 7.21 | 0.47   | 2.27             |

5. Admixture Rheoplast PCE 3240 produced by Rheoplast LTD. Mixture proportions are shown in Table 4.

Table 4. Mixture proportions.

| Ingredient                               | Content [kg/m$^3$] |
|------------------------------------------|--------------------|
|                                           | 150/300 300/150 170/175 170/280 230/115 230/220 |
| Cement CEM I 42.5N                       | 150 300 170 170 230 230 |
| Slag                                     | 300 150 175 280 115 220 |
| Sand with grain size of 0-1 mm            | 397 397 257 415 347 380 |
| Sand from limestone crushing screenings   | 552 552 606 571 623 556 |
| Crushed trap rock with grain size:       |                    |
| 4-11 mm                                   | 785 785 500 753 500 820 |
| 11-22 mm                                  | - - 483 - 395       |
| Admixture Rheoplast PCE 3240              | 1.65 1.65 4.83 7.425 4.14 8.33 |
| Water                                     | 165 165 165 165 175 155 |
| Total:                                    | 2351 2351 2361 2361 2389 2369 |
| Slump class                               | S1 S1 S1 S2 S1 S2 |

Compressive strength [MPa] at the age of [d]:

| Age | Compressive strength |
|-----|----------------------|
| 7   | 32.7 40.2 29.4 33.8 30.4 34.2 |
| 28  | 48.5 62.1 44.3 57.7 46.5 58.8 |
| 90  | 60.2 82.0 58.6 77.5 60.4 75.2 |

$Q_{\text{max}}$, MJ/m$^3$

* The value above the line is the cement consumption; below the line is the consumption of ground granulated blast furnace slag in kg/m$^3$.

3. Test results and discussion

Compressive strength of concrete was determined on cubes with a size of 100x100x100 mm according to Russian State Standard GOST 10180-2012 “Concretes. Methods for strength determination using reference specimens”.

Heat release $Q$ was determined according to EN 196-9:2010. The heat release of concrete was determined by the thermos method at an initial temperature of 20 ºC. After that, the heat release of concrete was recalculated to the isothermal hardening mode at a temperature of 20 ºC.

We used the hypothesis [37] in which ratio of the heat release rates and corresponding terms $t_2$ and $t_1$ remains constant at moments of equal heat release at $Q_i = Q_2$:

$$\frac{\partial Q}{\partial t_1} = \frac{\partial Q}{\partial t_2} = f_t = \text{const}$$  \hspace{1cm} (1)

The temperature function $f_t$ was calculated by the formula:

$$f_t = 2^\frac{\Delta t}{\varepsilon}$$  \hspace{1cm} (2)

where $\varepsilon$ is the characteristic temperature difference. If $t_1 - t_2 = \varepsilon$, then $f_t = 2$. This means if the temperature rises by $\varepsilon$ degrees, the rate of heat release will double.
Three identical samples of each concrete mix were tested. The readings of the temperature sensors were recorded by the datalogger every 30 minutes.

The heat release $Q_{\text{max}}$ (see Table 4) is a parameter of the I.D. Zaporozhets equation [38]:

$$Q = Q_{\text{max}} \left[1 - (1 + A_t \tau)^{-\frac{1}{m}}\right]$$

(3)

The value of $Q_{\text{max}}$ in equation (3) is the total amount of heat that 1 m$^3$ of hardening concrete will release in an infinite period of time; $A_t$ is the heat release rate coefficient that characterizes the heat release rate at a given constant temperature $t$; $m$ is the order of the cement hydration reaction. The order of the cement hydration reaction for Portland cement is between 2 and 2.3.

The results of the heat release determinations of concrete are presented in the form of graphs of the dependence of the amount of heat in MJ released by 1 m$^3$ of concrete (Figures 1-3).

The results of determinations the heat release of concrete are shown in the plot of quantity of heat (MJ) released by 1 m$^3$ of concrete versus time (see Figures 1-3).

The difference between the concrete mix 150/300 and the concrete mix 300/150 was cement to slag ratio, but the total binder consumption was the same – 450 kg/m$^3$. The heat release curves of these concrete mixes are presented in Figure 1.

![Figure 1](image)

**Figure 1.** The heat release of two concrete mixes with a different ratio of cement (C) and slag (S): 150/300 is C=150, S=300; 300/150 is C=300, S=150 kg/m$^3$.

The ratio of the heat release of the mix 150/300 to the heat release of the mix 300/150 after 5 days was 1.5 and the same ratio at infinity was 1.55. However, the ratio of the compressive strength of these mixes (see Table 4) after 7 days was 1.23, after 28 days was 1.28 and after 90 days was 1.36. That means the heat release decreased by 50 – 55 % and the compressive strength decreased by only 23 – 36 % because of using slag as a cement replacement material. This can be used during concrete casting to reduce the heat release of concrete. It could also reduce thermal cracking in concrete. For other experiments, we used cement consumption of 170 kg/m$^3$ and 230 kg/m$^3$ (Figure 2 and Table 4).

As can be seen, there was no similar decrease in the heat release and compressive strength. Nevertheless, there were two differences from previous experience: 1) the slag was added in excess of cement consumption; 2) two mixes with C=170 had a difference in polycarboxylate content about 1.5 times and two mixes with C=230 had a difference about 2 times; 3) two mixes with C=230 had a difference water-cement ratios.

Heat release curves for concrete with relatively low cement consumption and increased slag consumption are shown in the Figure 2.
After that, we conducted the third experiment. Five mixes were tested with the same materials, but without the coarse aggregate and the admixture. The difference between the concrete mixes was cement to slag ratio. Other parameters were the same - total consumption of the cement and the slag of 500 kg/m$^3$, w/c ratio of 0.5 and sand content of 1516 kg/m$^3$. Concrete samples were tested for the heat release, as described above, and for compression and flexural strength. The heat release curves of these concrete mixes are presented in Figure 3.

The heat release in Figure 3 is a calorific value $q=Q/(C+S)$ per 1 kg of mixed binder consisting of the cement and the slag.

The heat release of the mixes with only slag can be considered equal to 0. The temperature of the slag rises by 1.5 °C when mixed with water. This relates more to the heat of wetting than to heat of hydration. The other curves are arranged in order of decreasing the slag content and increasing the cement content from the top down.

The composition of the mixed binder, the strength of the fine-aggregate concrete and heat release parameters are showed in Table 5.
Table 5. The composition of the binder and the concrete properties.

| Composition of the binder [%] | Strength [MPa] | Heat release parameters | Autogenous shrinkage [mm/m] | Density [kg/m³] |
|-------------------------------|----------------|-------------------------|-----------------------------|----------------|
|                               | Flexural strength | Compressive strength | $q_{max}$ [kJ/kg] | $A_t$ [d⁻¹] | 28 days | 52 days |
| 0                             | 0               | 0                       | 0                         | 0              | -       | -       | 2174   |
| 25                            | 75              | 7.2                     | 62.8                      | 200            | 0.41    | 0.129   | 0.166  | 2164   |
| 50                            | 50              | 8.1                     | 71.5                      | 250            | 0.68    | 0.157   | 0.206  | 2159   |
| 75                            | 25              | 9.6                     | 82.6                      | 300            | 0.86    | 0.102   | 0.134  | 2165   |
| 100                           | 0               | 9.3                     | 79.6                      | 345            | 0.92    | 0.062   | 0.113  | 2166   |

The Table 5 shows that the maximum heat release is almost directly proportional to the proportion of cement in the binder. In addition, the concrete strength increases and the autogenous shrinkage decreases with a rise in the cement content.

The graph at the Figure 4 was performed to compare the results of determining the heat release and the strength depending on the content of the slag in the binder. The graph shows the relative values of $q_{max}$, $A_t$, and compressive strength $R_c$. 100% on the graph corresponds to the composition of the binder in which there is no slag, that is, the binder consists only of cement (100%).

![Figure 4](image.png)

Figure 4. The changing in the relative values of heat release and concrete strength depending on the content of slag in the binder: 1 is $q_{max}$; 2 is $A_t$; 3 is $R_c$.

The Figure 4 shows that the concrete strength is increasing rather than decreasing if the slag content is up to 30%. This area is shown in red in the Figure 4. At the same time, the heat release and its speed is falling by about 15-18 %. Thus, it is possible to reduce the heat release of concrete without losing its strength. This is especially important in terms of its thermal crack resistance. If the slag content is over to 30%, then the concrete strength is decreasing, but much slower than the heat release of concrete.

The effect of cement replacement by slag in the mixed binder on the reduction of the release and loss of the concrete strength is showed in Table 6. The minus sign in the Table 6 shows that the compressive strength of concrete increased by 3.8%, while the heat release decreased by 13%. This happened when 25% of the cement was replaced by slag. The compressive strength decreased by 10.2% at the slag content of 50% and the compressive strength decreases by 21.1% at the slag content of 75%. However, in these two cases, the heat release decreased 2 times more.
Table 6. Reduction of heat release and strength of the concrete depending on the slag content

| The amount of cement replaced by slag [%] | Heat release reduction [%] | Compressive strength reduction [%] | Flexural strength reduction [%] |
|-----------------------------------------|---------------------------|-----------------------------------|-------------------------------|
| 0                                       | 0                         | 0                                 | 0                             |
| 25                                      | 13.0                      | -3.8                              | -3.2                          |
| 50                                      | 27.5                      | 10.2                              | 12.9                          |
| 75                                      | 42.0                      | 21.1                              | 22.6                          |
| 100                                     | 100                       | 100                               | 100                           |

4. Conclusions
1. Concrete was tested for strength, heat release and shrinkage. Several mixes with partial replacement of cement by ground granulated blast furnace slag from the «İskenderun Demir ve Çelik A.Ş.» (İskenderun, Turkey) were used for the testing.
2. The heat release is reduced by up to 50% and the loss of strength is not more than 36%. This is the result of an increase in the slag content in the mixed binder (cement + slag) and a decrease in the cement content. The replacement of the cement content by the ground blast furnace slag is recommended to reduce the heat release of concrete, in order to increase its thermal crack resistance.
3. The optimal slag content in the mixed binder is 25%. There is an increase in concrete strength by 3-4% and a decrease in heat release by 13% compared with the cement binder. All tested concrete mixtures with cement replacement by slag have a decrease of the heat release, which is greater than a decrease in the concrete strength.
4. The replacement cement of the slag leads to an increase in autogenous shrinkage. If the binder contains 50% of the slag, the highest value of autogenic shrinkage is observed. This value is approximately 2 times greater than the shrinkage of concrete on the cement binder. If the binder contains 75% of the slag, the shrinkage is less.

Further research on this topic may be experimental studies of the slag as a partial replacement for coarse aggregate for concrete. If presoaked aggregate is added to the concrete mix, this will create “internal curing” for the concrete [39, 40].

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