Heat release of expanded-clay concrete

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Abstract. The subject of research is expanded-clay concrete with additives of ground granulated blast-furnace slag, silica fume, superplasticizer and air-entraining admixture. The heat release of concrete is investigated depending on the concrete composition (cement, water cement ratio, expanded-clay), additives (slag, silica fume) and admixtures (superplasticizer, air-entraining agent). This study is a part of research on the design concrete mixture with strength class C35/45 and high workability for 3D printer. It was confirmed that the cement content and water cement ratio impact on the integral value of the heat release per unit mass of cement. This value decreases with increasing cement content. The reason for this is that the heat generated by concrete, with constant W/C and other equal conditions, increases linearly with increasing the cement content.

Key words: Claydite Concrete, Expanded-Clay Concrete, Cement, Superplasticizer, Heat Release, Heat of Hydration, 3D-printer, Multifactorial Regression Analysis, Ground Granulated Blast Furnace Slag, Silica Fume.

1 Introduction

Heat release concrete properties play an important role for conventional and additive (3D printing) concrete technologies [1]. Cracks appear in hardening concrete because of the heat of hydration of cement. These cracks are caused by uneven and moderate temperature deformations [2-3]. There are different technical solutions for controlling the thermal conditions of hardening concrete and reducing temperature differences [4-6].

For additive technologies, the rheological properties of the concrete mixture are also significant [7-8]. In this paper, rheological properties are not considered. The rheological properties of the concrete mixture can be controlled by various additives. They may be included in the mixture to improve certain characteristics of the concrete mix or concrete structures [9].

Experimental studies [10-11] showed that the addition of silica and nanoclay improved the formability of the fresh printing mixture, while a slight improvement was observed as a result of the addition of polypropylene fiber [12]. Other mineral admixture (fly ash, blast furnace slag, limestone, silica, silica fume, nanosilica, granite, perlite, vermiculite, etc.) also improved the properties of concrete [13-15].

3D printers create of an object based on a digital 3D model [16-17] by adding material to the object layer by layer. Therefore, the heat release significantly determines the process of shrinkage and cracking during curing period of concrete [18].

The properties of concrete mix for 3D printing technology makes many demands. The mixture must have a certain viscosity and moldability to maintain the required shape during printing. In addition, the mixture must have workability for extrusion. It should also be fast setting, so as not to lose shape without formwork [19-20]. If it is necessary for concrete to have greater strength, steel
reinforcement, fiber or glass-fiber are added to the mixture [21-26]. Possible flexural strength is up to 30 MPa and compressive strength is up to 80 MPa in the case of using carbon, glass and basalt fibers with a size of 3-6 mm [27-28]. It is possible to use lightweight steel concrete structures consisting of monolithic concrete, profiled steel and fiber-cement sheets [29-30].

A study [31] investigated adhesion between the layers of 3D printed concrete. It was found that the adhesion between the layers decreased with increasing time interval between lay-up. The interlayer bonds can be strengthened with cement paste at the interface [32]. This solution minimized voids and increased the adhesion area.

Good extrudability and buildability were achieved when the yield strength of the material was in the range of 1.5-2.5 kPa [33]. The material did not have enough strength for maintain shape if the yield strength was below this range. Nevertheless, the material extrudability was difficult if the yield strength was above this range.

However, the heat release of concrete has not been studied in detail for construction 3D printing. It made this study relevant.

The subject of research in this paper is expanded-clay concrete with additives of ground granulated blast-furnace slag, silica fume, superplasticizer admixture and air-entraining admixture.

The objectives of the work is analysis of expanded-clay concrete composition influence on the heat release of concrete.

2 Materials and methods

The Fly ash aggregate was tested in Peter the Great St. Petersburg Polytechnic University (Russia).

Concrete mixture consisted of:
1. Portland cement PC 500-D0-N produced by OJSC MORDOVCEMENT (Mordovia, Russia). Fineness of the cement is 97.1 %. Mineralogical composition of the cement are presented in table 1.

| Mineralogical composition of the cement [%] |
|--------|--------|--------|--------|
| C₃S  | C₂S  | C₃A  | C₄AF  |
| 60.8 | 16.6 | 5.8   | 12.8   |

2. Natural sand. The sand has fineness modulus from 2 to 2.5.

3. Expanded clay gravel produced by OOO SUOR (Novocheboksarsk, Russia). Size fraction is 0-20 mm, bulk density is 800 kg/m³ and cylinder strength is from 5.5 to 6.5 MPa.

4. Silica fume MKU-85 produced by Yurga division of Kuznetskie Ferrospalv (Yurga, Russia). Specific surface area is 15 m²/g. Content of SiO₂ is 91.2 %.

5. Ground granulated blast furnace slag produced by PJSC Mechel (Russia). Chemical composition of the slag are presented in table 2.

| Chemical composition of the ground granulated blast furnace slag. |
|------------------------|--------|-------|--------|--------|--------|--------|--------|
| S  | K  | SiO₂ | CaO | MnO | Al₂O₃ | MgO | TiO₂ | FeO |
| 0.710 | 1.54 | 38.90 | 40.50 | 0.57 | 10.50 | 7.50 | 0.73 | 0.63 |

6. Superplasticizer Sika ViscoCrete E78 RC/A.
7. Air-entraining admixture Sika AER 200-C.

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 [34] in which ratio of the heat release rates and corresponding terms $\tau_2$ and $\tau_1$ remains constant at moments of equal heat release at $Q_1 = Q_2$:

\[
\frac{\partial Q}{\partial \tau_2} = \frac{\tau_2}{\tau_1} = f = \text{const}
\]
The heat release data of expanded-clay concrete are presented in table 3. 

### 3 Results and discussion

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

$$f_t = t_{1/2}$$  \hspace{1cm} (2)

where $\varepsilon$ is the characteristic temperature difference. If $t_{1/2} = t$, when $f_t = 2$. 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. Heat release per unit mass of cement $q = Q/C$ in tested mixes was characterized by two parameters of the I.D. Zaporozhets equation (3):

$$Q = Q_{\text{max}} \left[ 1 \left( 1 + \frac{t}{A_t} \right)^{\frac{1}{m}} \right]$$  \hspace{1cm} (3)

where $A_t$ is the heat release rate coefficient that characterizes the heat release rate at a given constant temperature $t$ (in this case $t=20 \, ^\circ\mathrm{C}$ and $A_t = A_{20}$); $m$ 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 values of $Q_{\text{max}}$ and $A_{20}$ were determined by experimental data.

| Table 3. Mixture proportions and the heat release of expanded-clay concrete. |
|---|
| Cement (C) [kg/m$^3$] | W/C | Expanded clay gravel [kg/m$^3$] | Sika VC E78 C [kg/m$^3$] | Sika AER 200- [kg/m$^3$] | Silica fume [kg/m$^3$] | Slag [kg/m$^3$] | $Q_{\text{max}}$ [kJ/kg] | $A_{20}$ [d$^{-1}$] |
| $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $Y_1$ | $Y_2$ |
| 375 | 0.445 | 0 | 4.5 | 1 | 0 | 60 | 400 | 1.45 |
| 375 | 0.45 | 0 | 5.25 | 0 | 0 | 60 | 380 | 1.65 |
| 430 | 0.43 | 130 | 4.5 | 1.45 | 43 | 70 | 392 | 1.45 |
| 435 | 0.425 | 276 | 4.34 | 1.53 | 44 | 70 | 420 | 1.23 |
| 440 | 0.461 | 347 | 3.96 | 1.38 | 44 | 70 | 423 | 0.8 |
| 450 | 0.438 | 115 | 4.32 | 1 | 45 | 80 | 393 | 1.25 |
| 450 | 0.511 | 520 | 4.05 | 1 | 45 | 70 | 395 | 0.9 |
| 460 | 0.374 | 267 | 4.15 | 1 | 46 | 80 | 360 | 2 |
| 460 | 0.439 | 185 | 4.4 | 0.8 | 46 | 70 | 420 | 1.25 |
| 465 | 0.35 | 545 | 3.75 | 0.75 | 40 | 0 | 335 | 0.9 |
| 465 | 0.443 | 295 | 4.9 | 1.4 | 46 | 70 | 430 | 1.15 |
| 465 | 0.35 | 545 | 3.75 | 0.75 | 40 | 0 | 330 | 1.1 |
| 470 | 0.483 | 270 | 4.23 | 1.4 | 47 | 69 | 420 | 1.05 |
| 470 | 0.309 | 602 | 5 | 0.55 | 44 | 0 | 355 | 1.5 |
| 475 | 0.314 | 502 | 4.5 | 0 | 44 | 0 | 350 | 1.7 |
| 475 | 0.34 | 602 | 5 | 0.55 | 44 | 0 | 360 | 1.3 |
| 475 | 0.318 | 520 | 5.5 | 0.55 | 44 | 0 | 360 | 1.3 |
| 475 | 0.34 | 560 | 3.7 | 0 | 45 | 0 | 317 | 1.4 |
| 485 | 0.429 | 430 | 4.35 | 0.85 | 50 | 70 | 330 | 0.86 |
| 485 | 0.404 | 530 | 6 | 0 | 45 | 110 | 380 | 2.5 |
| 490 | 0.414 | 351 | 5.8 | 1 | 48 | 68 | 370 | 1.35 |
| 520 | 0.296 | 486 | 7.6 | 1.25 | 50 | 60 | 345 | 1.1 |
| 520 | 0.337 | 504 | 6.7 | 0 | 50 | 100 | 325 | 3.3 |
| 520 | 0.379 | 400 | 7.5 | 0 | 45 | 60 | 350 | 1.3 |
| 520 | 0.404 | 556 | 6.4 | 0 | 50 | 50 | 330 | 2.8 |
| 520 | 0.41 | 428 | 4.9 | 1.5 | 50 | 70 | 358 | 1.55 |
| 550 | 0.351 | 512 | 6.25 | 0 | 50 | 50 | 310 | 1.05 |
The influence of independent composition parameters \((X_1, \ldots, X_7)\) on the heat release parameters \((Y_1, Y_2)\) was determined by multivariate analysis based on linear regression.

The linear regression equations for the heat release parameters of concrete \(q_{\text{max}}\) and \(A_{20}\) were obtained. Importance factors are presented in table 4.

| \(q_{\text{max}} = f(X_1, \ldots, X_7)\) | F-statistics | F-significance | \(R^2\) |
|---|---|---|---|
| 9.70 | 2.95E-05 | 0.7725 |

| \(A_{20} = f(X_1, \ldots, X_7)\) | 3.63 | 0.0109 | 0.5598 |

Linear regression graphs for the most significant factors \(X_1, X_2,\) and \(X_5\) of the response function \(Y_1 = q_{\text{max}}\) are shown in figure 1.

![Figure 1](image-url)

**Figure 1.** Dual regression plots for the dependence of \(q_{\text{max}}\) versus cement content, water-cement ratio and admixture Sika AER 200-C content.

As a regression analysis has shown, the total integral value of the heat release per unit mass of cement \(q_{\text{max}} (Y_1)\) depends on three factors: the cement content \((X_1)\), the water cement ratio \((X_2)\) and the admixture Sika AER 200-C content \((X_3)\). Figure 1 shows a significant scattering of experimental points, but a certain tendency is observed. The decrease in the heat release per unit mass of cement \(q/Q/C\) with an increase in cement content is a well-known position. The heat \(Q\) produced by concrete, with constant W/C and other equal conditions, increases linearly with an increase in the cement content C [36-37]. This explains the law of mass action from chemical kinetics.

### 4 Conclusions

A multivariate analysis of experimental data on the influence of seven factors of concrete mixture (cement, water cement ratio, expanded clay, ground granulated blast-furnace slag, silica fume, superplasticizer, air-entraining admixture) on the heat release of concrete was carried out. The results obtained lead to the following conclusions:

1. The cement content and water cement ratio impact on the integral value of the heat release per unit mass of cement. This value \(q=Q/C\) decreases with increasing cement content. The reason for this is that the heat \(Q\) generated by concrete, with constant W/C and other equal conditions, increases linearly with increasing the cement content C. W/C has a positive effect on the heat release of concrete. This explains the law of mass action from chemical kinetics.
2. The air-entraining admixture Sika AER 200-C increases the heat generation by concrete. This is due to the chemical interaction between the admixture and cement hydration products with the formation of thermodynamically more stable compounds.

3. The influence of these seven factors on the rate of heat release, and, consequently, on the hydration of cement has not been established.

Further research on this topic may be experimental studies of cold-bonded fly ash aggregate concrete for 3D printer. Fly ash can be used as an additive in the mix [38] or as a large aggregate [39]. If presoaked aggregate is added to the concrete mix, this will create “internal curing” for the concrete and reduce cracks caused by the heat release [40].

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