Jacek Gołaszewski
Grzegorz Cygan

Department of Building Materials and Processes Engineering, Faculty of Civil Engineering, Silesian University of Technology

The concept of the composition of self-compacting concrete with low hardening heat

Kształtowanie właściwości betonów samozagęszczalnych o niskim cieple hydratacji

Abstract

This paper presents a proposal for shaping the properties of green self-compacting concrete, mostly focussing on minimising the amount of clinker in concrete and obtaining lower hardening temperatures. The main application of this SCC would be in constructions build during summer, as well as in massive and semi-massive structures. In these kinds of constructions, thermal effects connected with cement hydration are of particular importance. The difference in temperature between the interior and the relatively fast cooling exterior of the concrete element leads to thermal stress. In extreme conditions, this can cause cracking within the entire bulk of concrete element, leading to a lowering of its durability and longevity.

Keywords: self-compacting concrete, heat of hydration, massive structures

Streszczenie

W artykule przedstawiono koncepcję doboru składników mieszanek betonów samozagęszczalnych o niskim cieple hydratacji. Takie mieszanki są wykorzystywane do realizacji konstrukcji masywnych, a także do realizacji prowadzonych w warunkach podwyższonych temperatur. W konstrukcjach masywnych, efekty cieplne związane z reakcją hydratacji mają szczególne znaczenie. Różnica temperatur pomiędzy wnętrzem a powierzchnią konstrukcji prowadzi do powstawania naprężeń termicznych. W ekstremalnych warunkach prowadzić to może do zarysowania konstrukcji w całej jej objętości. Prowadzi to do obniżenia trwałości konstrukcji, a w przypadku masywnych fundamentów obciążonych dynamicznie może je całkowicie dyskwalifikować.

Słowa kluczowe: beton samozagęszczalny, ciepło hydratacji, konstrukcje masywne

1. Introduction

The composition and constituents of SCC are chosen on the basis of its rheological properties, taking into consideration the requirements of the construction with regard to concrete. SCC has to fulfil the following requirements: fresh concrete fluidity, which has to guarantee swift and precise filling of the form and covering of reinforcement; self-deaeration, which is its ability to quickly remove air from the concrete mix; stability, which is the resistance of the concrete mix to segregation [1].

The requirements of concrete mix fluidity and self-deaeration can be fulfilled by lowering the yield and plastic viscosity of the fresh concrete (or increasing the spread D_{max} and reducing the spread time T_{500} according to a slump flow test). The lower the yield, the lower the height of a concrete mix column which causes its flow, and the faster and more efficient its deaeration and levelling in a form or formwork. The lower the plastic viscosity of the concrete mix, the shorter the time concrete mix needs to fill a form and deaerate. Unprompted sedimentation of the aggregate decreases when the plastic viscosity increases; however, it increases with larger aggregate grains and higher differences between the densities of the aggregate and the cement paste. Achieving a compromise between the conflicting requirements of fluidity and self-compaction, thus obtaining suitable rheological properties of the concrete mix, is the single biggest challenge during the process of designing a concrete mix. It is assumed that for the sake of the fluidity requirement, the yield should be as low as possible. At the same time, the plastic viscosity should be chosen so that the concrete mix properly and quickly fills the mould and that the air is effectively removed with a minimum of segregation.

The necessity to meet the rheological criteria determines the need for a specific composition and combination of constituents of the self-compacting concrete. First and foremost, assumed are: small w/(c+a) ratio (w – water, c – cement, a – mineral additives), and a large amount of fine fraction (< 0.125 mm), which includes fine aggregate, as well as cement and mineral additives (stone powder, ground granulated blast furnace slag, fly ash and others). Mineral additives allow to increase the amount of cement paste without increasing the amount of cement over the necessary minimum. Due to the fact that the presence of additives helps to reduce the amount of cement in the concrete, the amount of heat generated during hydration is reduced. By properly choosing the type and amount of additives, it is possible to regulate the technical properties of concrete. A low w/c ratio and a high content of dust fractions reduce the amount of free water in the concrete mix – this increases its resistance to segregation and sedimentation.

Typical self-compacting concrete is characterised by a w/c ratio < 0.50, w/(c+a) < 0.35, a fine fraction content from 500 to 600 kg/m³ and a volume of cement paste from 300 to 400 dm³/m³ or even higher. The right fluidity is obtained through use of effective superplasticizers, usually based on polyethers. Moreover, in order to reduce the risk of segregation of the concrete mix and to obtain an appropriate degree of flow, rounded, regularly shaped gravel is used; its maximal size should not exceed 20 mm (usually 10–16 mm) and its sand content should be 40–50%. In order to eliminate or reduce the segregation and the leakage of cement paste from fresh concrete, and to lower its pressure on the formworks, it is
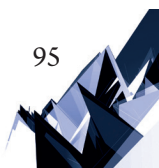
recommended that viscosity increasing admixtures be used. The presence of such admixtures also decreases the susceptibility of fresh concrete to changes in the amount of water. Due to the technological simplicity of adding admixtures to a degree, they can pose as an alternative to the use of mineral additives – they allow the improvement of the stability of the fresh concrete without the need to interfere with its basic composition.

Proper selection of the constituents of the fresh concrete is also essential for the building of massive structures. The concrete composition is calculated so that the amount of heat generated by cement hydration is minimised whilst taking into consideration the requirements of the concrete with regard to construction [2]. Due to the fact that cement is the constituent that determines the amount of generated heat, it is necessary to use cements which produce low levels of hydration heat and to try to limit their content to the necessary minimum.

In practice, for concrete in massive structures, amount of cement for 1 m³ of concrete does not exceed 300 kg/m³. In order to further limit the amount of heat generated during the hardening of the concrete, mineral additives are used as a substitute for the part of cement – the best results are obtained by using fly ash or ground granulated blast furnace slag. Because of the necessity to limit concrete shrinkage and to provide adequate impermeability of the cement matrix and adequate durability of the concrete construction, it is best to use a w/c ratio lower than 0.5 (however, to keep of the amount of heat generated to a minimum, the w/c ratio can be higher). Because of the need to obtain this ratio, it is necessary to use plasticisers and superplasticizers to acquire the right workability. Retarding admixtures are used in order to delay the setting time and to spread the heat production over the course of time.

Due to the minimisation of the amount of cement (and cement paste) it is beneficial to use aggregate with the largest possible grain size and an amount of sand not exceeding 30–35%. It is worth noting that because of the technological factors and the possibility of causing tension in the element, aggregate grains should not be larger than 31.5 mm. An important consideration is the choice of an aggregate which has appropriate levels of thermal conductivity and coefficient of thermal expansion. The best properties in this regard are displayed by gravel aggregate, and to a lesser extent granite and limestone aggregate.

As can be observed, the compositions of both SCC and concretes for massive structures easily fall within the definition of 'green concrete' [3, 4]. Obtaining SCC that generates low hydration heat is not, however, an easy task. Primarily, the amount and composition of the cement paste must be optimised in such a way that allows the fulfilling of both the requirement of self-compaction (in which a higher quantity of cement paste is desirable) and the minimisation of the amount of heat generated (in which a lower quantity of cement paste is desirable). Another important consideration is the choice of aggregate grading – this choice should be made in such a way that the requirements of self-compaction can be met with the realistically lowest content of sand and the largest possible size of aggregate grains. The general concept of the composition of SCC which generates low levels of hydration heat is presented in Fig. 1.

w/(c+a) = 0.35 − 0.45, (w/c = 0.35 − 0.60)
Water -160 − 180 dm³/m³
Fine fraction ≅ 450 kg/m³
Compromize

Paste volume - app. 300 dm³/m³
Segregation resistance, bleeding

Coarse aggregate max. 0-16 mm of minimal voids
Segregation resistance, paste volume limitation

Low heat, low clinkier cement + fly ash + ground stone
Depending on technical requirements

Superplasticizer PCE + plasticizer/retarder
(other admixtures if necessary)
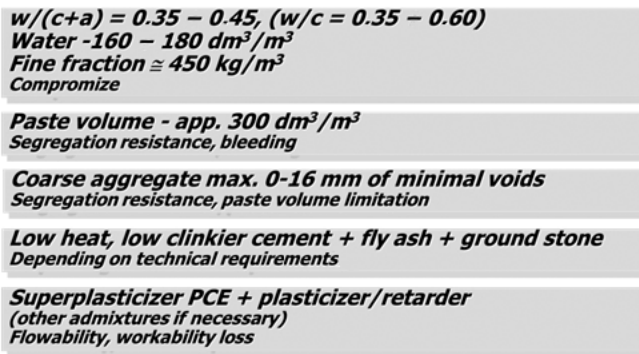*Flowability, workability loss*

Fig. 1. The technical requirements green SCC generating low hydration heat

It is assumed that the amount of the cement paste in this concrete should not exceed a level of around 280–300 dm^3/m^3, meaning it should not vary from the amount of cement paste in mechanically compacted concrete. With this amount of cement paste, by appropriately choosing the w/c ratio, type and amount of cement and type of mineral additives, it is possible to more or less freely shape the rheological properties of the fresh concrete, the amount of heat generated during the hardening process, and the properties of the hardened concrete. It is also possible to fulfil the requirements of concrete standards that apply to 300–350 kg/m^3 of cement with a w/c ratio of 0.45–0.60 which result from the exposition class dependant on the environmental conditions according to PN-EN 206.

It should be noted that using a w/c ratio > 0.5 allows lowering the degree of hydration heat generated and inhibiting the kinetics which result from hydration heat generation in the early phase of hydration – this is beneficial due to the early thermal effects in the massive concrete structure. If expected properties of hardened concrete allow, it is beneficial to set as high a w/c ratio as possible.

The necessity to guarantee the required stability of the SCC mix imposes the use of aggregate with a maximal grain size of 16 mm. This presents certain problems with regard to the minimisation of the amount of cement paste and requires careful selection of the aggregate grading to minimise the content of empty voids. Use of gravel aggregate is the optimal choice considering the requirements for SCC and massive concrete structures.

It is assumed that the required rheological properties of fresh concrete can be obtained through the use of a carefully selected superplasticizer, thus avoiding the use of viscosity enhancing admixtures. It should be noted that air-entraining of fresh concrete can be used as a way of decreasing the amount of cement (binder) in the concrete – this is beneficial with regard to the amount of heat generated (however, it may impede the extent to which its workability can be shaped). In order to achieve this effects, air-entraining cements or admixtures may be used.

2. Research methodology and compositions of mixtures

During the research, the possibility of obtaining self-compacting concrete which generates low levels of hydration heat according to the above-mentioned requirements was investigated. When selecting the amount and type of binder, the objective was to minimise the use of clinker in the concrete; therefore, cements with low levels of clinker were used – these included new, air-entraining cements which had not been previously used in Poland. The amount of cement was also minimised by substituting it with various combinations of high-calcium fly ash, limestone and silica fume.

Table 1. Composition of concrete

Content	B0	B1	B2	B3	B4	B5	B6
CEM I 52.5 N	451						
CEM III/B 42,5 L-LH		306			238	250	253
CEM V AS-V			297				
CEM V AS-V AEA				277			
Calcareous Fly Ash					104		
Quartz Meal						135	
Limestone							125
Sand 0-4	800	969	946	881	998	997	880
Coarse aggregates 4-11	437	363	354	330	372	374	420
Coarse aggregates 8-16	538	451	440	410	468	464	490
Water	171	193	187	174	151	158	160
SP Glenium SKY 591 [kg]	3.91	2.90	3.89	5.05	7.78	5.45	5.28
$w_{eff}/(c+a)$	0.38	0.63	0.63	0.63	0.44	0.41	0.42
w_{eff}/c	0.38	0.63	0.63	0.63	0.63	0.63	0.63
Volume of cement paste $[dm]^3$	320	294	289	268	270	293	291

About five million tons of calcareous fly ash is produced annually in Poland as a result of brown coal combustion in conventional boilers. The results of studies [5, 6] show no negative influences of HCFA on the properties of hardened concrete. The main problem with the practical use of HCFA is that its inclusion significantly worsens the workability of fresh concrete, especially in the aspect of workability loss.

However, it has shown that the negative influence of CFA on the workability of fresh concrete may be reduced through the application of a grinding process and even the obtaining of SCC with HCFA is possible [4, 5]. Among the variants of concrete tested (Table 1) there were concrete mixes which included sand and gravel aggregate with the fraction grading shown in Fig. 2. SCCs were designed using the method presented in [7].
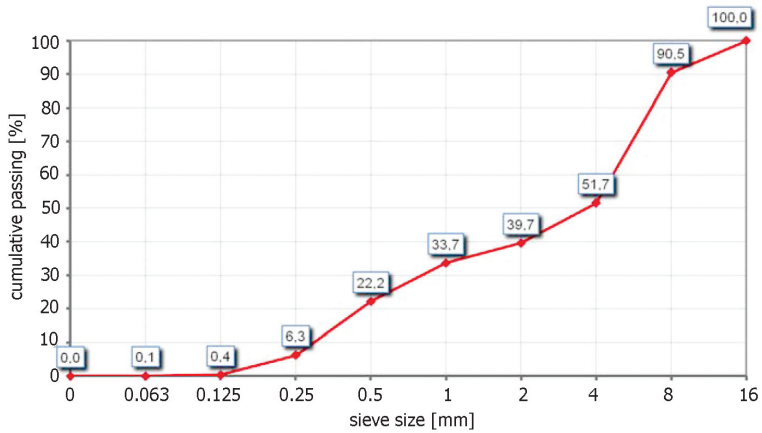
Fig. 2. Aggregate grading curve

Fresh and hardened concretes were tested for:

▸ Properties of fresh SCC – measurements were performed at a temperature of 20°C at 5 and 60 min after the completion of mixing using the slump-flow test according to EN 12350-8. The stability of each mixture was evaluated using the Visual Stability Index (VSI; according to ACI 237 R-07; 2007). Additionally, the air content in the mixture at 5 min after mixing was determined according to EN 12350-7.

▸ Setting time of concrete – measurements were performed using an ultrasonic method by means of the Schleibinger Vikasonik system. The transmitter and receiver were placed on the sides of the 25 cm cubes which were tested for the progress of concrete hardening temperature.

▸ Progress of concrete hardening temperature – measurements were performed on 25 cm cubic samples on a face which was insulated using polystyrene foam coating with a thickness of 100 mm and a thermal conduction coefficient of 0.044 W/m·K (Fig. 3). Temperature measurements were taken from the centre of the cubes. The external temperature during the performing of measurements was 20°C.

Fig. 3. Sample of fresh concrete with thermal insulation and the Vikasonic system as prepared for measurement

- ▸ Compressive strength after 2, 7 and 28 days – measurement were performed according to PN-EN 12390-3, samples were cured according to PN-EN 12390-2.
- ▸ Hydration heat – for binders and admixtures used in the tested concretes, hydration heat and hydration kinetics were measured using the Tam Air isomeric calorimeter produced by TA Instruments. Measurement was performed on the cement (binder) paste over a 72-hour period with superplasticizer content analogous as in concrete. Measurement was performed at a temperature of 20°C.

3. Test results and discussion

The obtained results are compiled in Tables 2 and 3. The highest amount of generated heat during the hydration process was clearly obtained for samples with the B0 binder (Portland cement CEM I and SP). Samples which contained the other binders produced significantly lower hydration heat and kinetic activity associated with its generation – the amount of heat generated is mainly dependent on the amount of cement clinker and specific surface area. The smallest amount of heat generated during the hydration of ground granulated blast-furnace slag cement occurred with samples using the CEM III/B 42,5 L-LH binders. Composite cement CEM V/A (S-V) with AEA has a lower amount of heat at the first stage of hydration than CEM V/A (S-V) without the addition of AEA.

Self-compacting concretes of slump flow class SF2 and viscosity VF2 were obtained. These properties were generally sustained at a stable level for at least one hour. This also applies to the concrete mixes which contained high-calcium fly ash (B4); however, in this case, it is necessary to increase the quantity of superplasticizer which is added. The concrete, excluding the concrete with air-entraining cement which has an air-content of 11%, has an air-content at the level of 2%. The use of cements with mineral additives in concrete composition and the introduction of mineral additives in place of portion of the cement delays the setting time in comparison with the SCC mixture with CEM I cement – the delay amounts to 50–100% (3–6 h). The longest delay was observed for concrete B4 with cement CEM V/A (S-V) with the addition of AEA.

Use of cement with mineral additives and mineral additives themselves have significantly lowered the maximal hardening temperature of concrete from approx. 60°C for concrete with cement CEM I to approx. 40°C for concretes with CEM V/A (S,V) and approx. 30°C for concretes B2, B4, B5 and B6 with CEM III/B. Using cement CEM III/B is particularly effective, whereas using mineral additives with this cement only influences the concrete temperature to a lesser degree. Using air-entraining cement affects the temperature of hardening to a rather small degree. Using cements CEM III/B and CEM V/A (S,V) did not significantly increase the time taken to reach the maximal temperature of concrete in comparison to CEM I concrete. However, in the case of using mineral admixtures as a replacement for cement CEM III/B, the maximal temperature was recorded to have been reached from 14 to 22 hours later than in the concrete with cement CEM I.

Table 2. Research results

Property	B0	B1	B2	B3	B4	B5	B6
Slump flow after 5 min [mm]	705	680	650	620	650	670	695
Slump flow after 5 min [mm]	680	670	600	550	600	660	670
Flow time T_{500} after 5 min [s]	2.3	2.7	3.0	2.1	6.0	5.2	5.4
Flow time T_{500} after 60 min [s]	2.7	2.9	3.2	4.0	7.4	6.7	7.0
Air content A_C [%]	2.1	1.5	2.5	11.0	1.3	2.0	1.7
Initial setting time [h]	6:36	10:04	9:52	17:09	12:00	10:12	9:43
Maximal temperature [°C]	57.9	34.8	39.7	37.2	32.2	30.0	29.8
Time of maximal temperature	29:54	36:55	33:50	35:41	51:28	45:56	43:56
Compressive strength after 2 days [MPa]	25.3	2.3	2.0	0.8	4.9	1.2	2.0
Compressive strength after 7 days [MPa]	48.6	25.4	22.7	13.5	36.0	31.0	29.4
Compressive strength after 28 days [MPa]	57.8	41.4	38.9	25.2	48.3	44.8	42.5

Table 3. Test results – cement + additive hydration heat [J/g]

Concrete	1h	2h	12h	24h	72h
B0	10.54	13.25	38.37	75.84	201.06
B1	8.95	10.92	22.70	32.31	151.64
B2	2.72	3.55	6.42	10.51	119.1
B3	3.77	5.21	9.56	17.48	120.02
B4	7.84	10.66	22.43	30.19	106.05
B5	6.70	8.41	13.31	19.69	81.83
B6	9.53	10.96	16.29	25.26	94.72

As could be expected, the compressive strength of concrete with cements CEM III/B and CEM V/A (S,V) and with the mineral additives is low and amounts from approx. 1 to 5 MPa after 2 days. However, after 7 days, it amounts to from 23 to 36 and the highest is for concrete containing CFA. After 28 days, there were compressive strengths of 38.9 MPa for CEM V/A and 42–47 MPa for CEM III/B concretes, which should be considered to be very satisfactory (usually concrete classes of up to C30/37 are specified for concretes used for massive structures). Due to high air entrainment, concrete with air entraining cement CEM V/A clearly has lower compressive strength in all measuring terms (after 2, 7, 28 days).

It was reconfirmed that despite the negative influence on workability, high-calcium fly ash which underwent the grinding process can be used for self-compacting concretes – its presence has either a zero or positive effect upon the remaining concrete properties. Air-entraining cements can be also used; however, in the case of these, problems may occur regarding control over the air content and, consequently, substantial losses in compressive strength – the air content is dependent upon the amount of cement and cannot be controlled by changing the amount of admixture.

4. Summary

Designed according to the proposed concept, self-compacting concretes are characterised by their low content of clinker, amounting to from 60 to 133 kg/m³, and their good strength properties. It can also be assumed that these concretes, due to their high content of blast-furnace slag, are also characterised by adequate durability; however, this requires further experimental verification.

It was proven that by optimising materials and concrete mix design, one can obtain green self-compacting concrete which is characterised by a low hardening heat and good mechanical properties over longer periods of hardening. This kind of concrete performs well, especially in massive structure elements. Ground high-calcium fly ash can be used for self-compacting concrete without negatively affecting the properties of the concrete after hardening.

Using air-entraining cements for concrete enables decreasing the amount of heat generated by concrete during hardening (approximately 7% lower maximal temperature of air entrained concrete was observed). The range of their use can also include concrete elements of considerable size; however, it should be note that when using air entraining cements, it is difficult to control air entrainment and the compressive strength of concrete.

References

[1] Szwabowski J., Gołaszewski J., *Technologia betonu samozagęszczalnego,* Polski Cement, Kraków 2010.

[2] Kiernożycki W., *Betonowe konstrukcje masywne,* Polski Cement, Kraków 2003.

[3] *N° 67. Guidelines for green concrete structures*, 60 p, May 2012.

[4] Suhendro B., *Toward Green Concrete for Better Sustainable Environment*, The 2nd International Conference on Sustainable Civil Engineering Structures and Construction Materials, Procedia Engineering Volume 95, 2014, 305–320.

[5] Ponikiewski T., Gołaszewski J., *The effect of high-calcium fly ash on selected properties of self-compacting concrete*, Archives of Civil and Mechanical Engineering, vol. 14, nr 3, 2014, 455–465.

[6] Ponikiewski T., Gołaszewski J., *The influence of high-calcium fly ash on the properties of fresh and hardened self-compacting concrete and high performance self-compacting concrete,* Journal of Cleaner Production, vol. 72, 2014, 212–221.

[7] Szwabowski J., Gołaszewski J., *Cement paste properties and paste-aggregate void saturation ratio as the factors governing the selfcompactness and compressive strength of concrete,* Cement Wapno Beton, R. 15, nr 2, 2010, 97–107.