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The influence of coarse aggregate shape on the properties of high-performance, self-compacting concrete

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Wpływ kształtu ziaren kruszywa grubego na właściwości samozagęszczalnych betonów wysokowartościowych

Abstract

High-performance, self-compacting concrete (HPSCC) represents a very significant step in the development of concrete technology. The most important features of SCC are specific rheological properties which include flowability, segregation resistance and passing ability. Therefore, a crucial requirement is to maintain an appropriate balance between the slump flow and plastic viscosity of concrete mixtures. In general, the rheological properties are modified by effective superplasticisers and a proper ratio of water to binder. The aim of this study is to focus on the important aspect of the impact of shape of the coarse aggregate on fresh concrete mixture properties and the strength of high-performance, self-compacting concrete (HPSCC).

Keywords: high-performance, self-compacting concrete (HPSCC), shape of coarse aggregate, flowability, strength of concrete

Streszczenie

Samozagęszczalny beton wysokowartościowy stanowi bardzo istotny krok w rozwoju technologii betonu. Najistotniejszą cechą betonu samozagęszczalnego są specyficzne właściwości reologiczne mieszanki, do których zaliczamy płynność, stabilność i zdolność do przepływu przez zbrojenie. Bardzo ważne jest więc zachowanie odpowiedniego balansu pomiędzy granicą płynięcia a lepkością plastyczną mieszanki. Na ogół właściwości reologiczne są modyfikowane poprzez stosowanie efektywnych superplastyfikatorów oraz odpowiedni stosunek wodno-spoiwowy. Celem niniejszej pracy jest zwrócenie uwagi na istotny aspekt wpływu foremności ziaren kruszywa na właściwości reologiczne świeżej mieszanki betonowej oraz wytrzymałość samozagęszczalnego betonu wysokowartościowego.

Słowa kluczowe: samozagęszczalny beton wysokowartościowy, kształt ziaren kruszywa, płynność, wytrzymałość betonu

1. Introduction

In recent years, we have observed a significant increase in the use of self- compacting concrete (SCC) in civil engineering. The advantages of SCC and the possibility of obtaining benefits from its use have already been described many times – this is confirmed by numerous applications of SCC. This technology is still evolving, covering an ever-wider range of applications, properties of concrete and even the use of unconventional materials to produce concrete mixtures such as recycled concrete aggregate and recycled glass aggregate [4, 6, 7].

Specific rheological properties of SCC are essential and they are substantially different from the properties of other concrete mixtures. Flowability, segregation resistance and passing ability are the most important features of SCC [15, 13,10].

Commonly known is that the cement paste content and water to binder ratio are there only two significant parameters of the mix design which affect to the appropriate rheological properties [5]. However, mixed design methods and testing procedures are still under development [14]. Mix design criterions are mostly focused on the type and mixture proportions of the constituents. Adjustment of the water/cement ratio and superplasticiser dosage is one of the key properties in the proportioning of SCC mixtures [1].

It is widely known that coarse aggregate is a substantial element which has an enormous impact on the strength of concrete. In civil engineering and concrete technology, the majority of igneous rocks aggregates like porphyry are used to produce high-performance concrete and special concretes. Here, the most well-shaped grains are desired with a shape similar to a sphere or a cube. The irregular grains, significantly different from the regular shape, has a greater area requiring increased amounts of cement and water [3]. The shape and particle size distribution of the aggregate is very important as it affects the packing and void content [16,9]. It has been found that a particularly great influence on the coarse aggregate strength occurs when the amount of irregular grains in coarse aggregate reaches 25-50%. For example, with a 50% share of irregular grains, the strength of basalt is reduced by 55% [17].

Due to the often overlooked issue of the impact of coarse aggregate grain shape on the rheological properties of fresh concrete mixtures and the strength of concrete in the case of self-compacting concrete, the author decided to pay attention to the essence of this factor.

2. Experimental programme

2.1. The specimens and materials

All specimens were produced from high-performance, self-compacting concrete. A total of forty-five cubic specimens were manufactured in a local laboratory and tested under uniaxial compression. Table 1 presents the details of the concrete mixture used in the research. In this study, the constituent materials making up the high-performance concrete were as follows: Portland-fly ash cement type I - CEM I 52.5R EXTRA, 0.32 water/binder ratio. SikaFume was used as a new generation concrete additive in fine-powder form based on silica fume technology [18]. Sika ViscoCrete-20 HE was used as a new generation powerful superplasticiser. Separated porphyry (ϕ4–8) and fine sand (ϕ 0–2) were used as aggregate.

Table 1. Proportions of concrete mixture ingredients

Mix type	Cement [kg/m³]	Sand [kg/m³]	Porphyre [kg/m³]	Water [kg/m³]	SikaFume [kg/m³]	Superplasticiser [kg/m³]	w/b ratio [-]
SCC	550	800	950	192	55	16.5	0.32

The feed material which was subjected to a process of shredding in a jaw crusher was porphyry (ϕ 16-24). The resulting product was properly separated by using slotted sieves in order to receive regular and irregular grains, in line with norm [12]. The study used grain sizes of ϕ 4-8mm only. Figure 1 presents regular and irregular grains of coarse aggregate used in the survey.

Three concrete mixtures were made: with regular grains only (SCC1); with irregular grains only (SCC2); with a mixture of 50% regular and irregular grains (SCC3). The shape of the coarse aggregate was the only variable value. Fifteen specimens of each concrete mixture were produced – all of the specimens were 100mm cubes. The concrete specimens were ripened in a water bath with a temperature of 20°C.

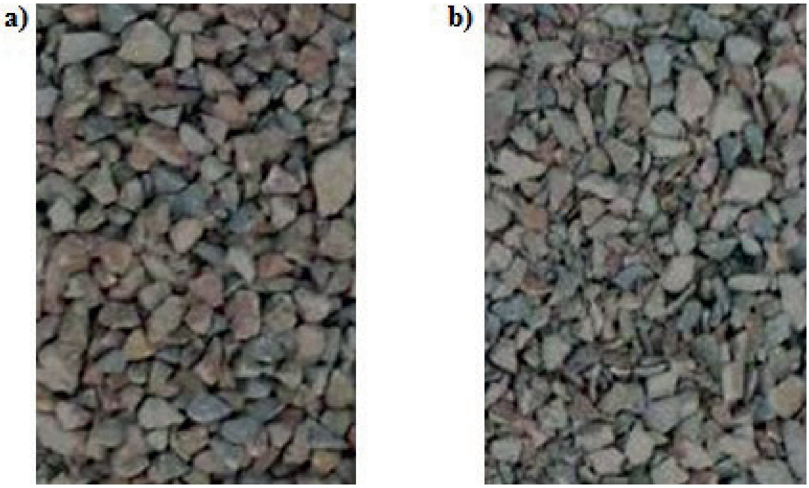

Fig. 1. Regular (a) and irregular grains (b) of coarse aggregate used in the investigation

2.2. Instrumentation and testing

The behaviour of the fresh self-compacting concrete was tested by using a slump flow test and a T_{500} test in line with norm [2]. These are quick and simple method, most frequently used both in laboratories and on construction sites – they provide a good assessment of deformability and can give visual information on stability.

Slump flow was calculated as the average value of the two measured diameters perpendicular to each other [2]:

$$SF = (d_1 + d_2)/2 \tag{1}$$

Viscosity of the fresh mixture was determined in the moment to reach diameter of 500mm by flowing concrete mixture.

Classifications used in the specification of SCC with respect to slump flow classes and viscosity classes are presented in Tables 2 & 3, respectively.

Table 2. Slump-Flow classes [15]

Class	Slump-Flow, [mm]
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

Table 3. Viscosity classes [15]

Class	$T_{500,}$ [s]
VS1/VF1	≤ 2
VS2/VF2	> 2

The uniaxial compression tests of the concrete specimens were performed using a servo-controlled MTS rock and concrete mechanics testing system (Fig. 2). The research was carried out at room temperature and humidity, with the constant axial stress rate of the specimens in all of the experiments of approximately 0.5 [MPa*s^{-1}]. The survey was conducted on the basis of norm [11]. Compressive strength was determined after seven, fourteen and twenty-eight days of ripening on a sample of five specimens each time.

Fig. 2. MTS testing system for uniaxial compression tests

3. Results and discussion

The experimental results from the tests are summarised in Tables 4 and 5. We can clearly observe that the shape of coarse aggregate grains has an impact on the rheological properties such as slump flow and the plastic viscosity of concrete mixtures. In case of SCC1, the maximum value of slump flow was obtained, this was 800mm. This is caused by the content of well-shaped grains and near-spherical grains in this concrete mixture which have a lower friction angle. The plastic viscosity of SCC1 was 3.2s and was the lowest value of all of the concrete mixtures. The highest value of this parameter was noticed in the case of SCC2. Additionally, the smallest slump flow was noticed for SCC2, this was 650mm. It is associated with the content of irregular grains – these have a higher friction angle than regular shape grains.

Table 4. Rheological parameters of fresh concrete mixtures

Mix type	T_{500} [s]	SF [mm]
SCC1	3.2 (VS2)	800 (SF3)
SCC2	8.1 (VS2)	650 (SF1)
SCC3	4.9 (VS2)	740 (SF2)

In each concrete mixture, there was no leakage of mortar – this proves that all of the concrete mixtures had been made properly. The sorting of the components did not occur (Fig. 3).

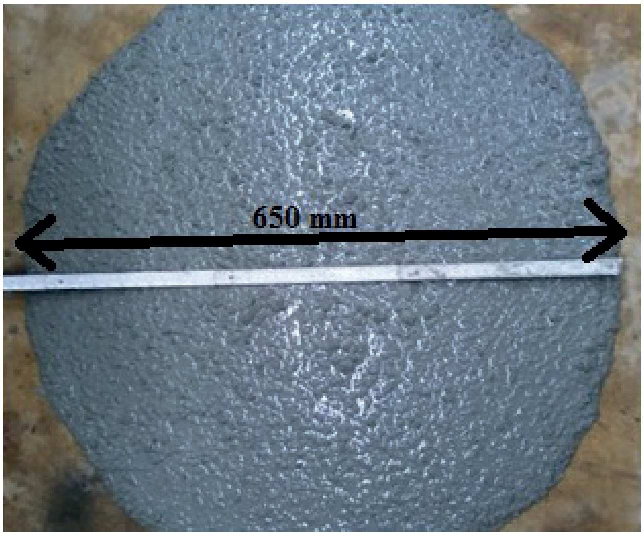

Fig. 3. Slump flow test for the SCC2 concrete mixture

It is important to note that all of the concrete mixtures were made with the same proportions of ingredients and a constant water/binder ratio– the only variable was the shape of the coarse aggregate. When analysing the results shown in Table 5, it should be noted that the shape of the grain has a huge impact on the strength of hardened concrete. There were significant differences in the strength of the concrete depending on the shape of the grains. The full twenty-eight-day compressive strength of concrete was greatest in the case of SCC3 (125.8MPa) and was 26% and 36% higher than SCC1 (100.2MPa) and SCC2 (92.2MPa), respectively. The standard deviation was in the range of 3 to 5MPa in each case.

Table 5. Compressive strength and density of concrete

Mix type	Density of concrete [kg/m^3]	Compressive strength at 7 days [MPa]	Compressive strength at 14 days [MPa]	Compressive strength at 28 days [MPa]
SCC1	2420	80.1	90.6	100.2
SCC2	2410	75.6	83.8	92.2
SCC3	2440	102.4	113.8	125.8

The type of aggregate has an impact on the density of concrete, which is related to the distribution of grains. The SCC3 concrete mixture, based on the coarse aggregate with 50% regular and 50% irregular grains, has the highest density whereas SCC2, with the irregular grains, has the lowest.

In all cases, the destruction proceeded in a conventional manner as evidenced by the formation of cones on the border of the uniaxial and triaxial stress state (Fig. 4).

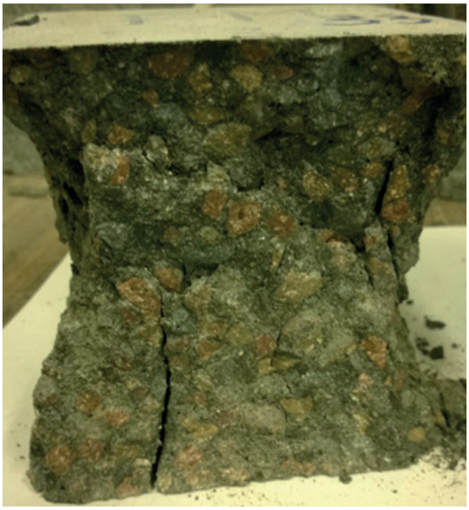

Fig. 4. Typical failure modes of SCC1

The use of irregular grains significantly affects the decrease in concrete strength by the low strength of the stack detrital aggregates and the formation of voids under the surface of irregular grains, what have been seen with the naked eye in the macroscopic analysis of destroyed samples in case of SCC2. In the case of SCC1 and SCC3, there were no air voids in the structure of the damaged concrete.

Figure 5 shows the increase of the compressive strength of concrete at the function of the time.

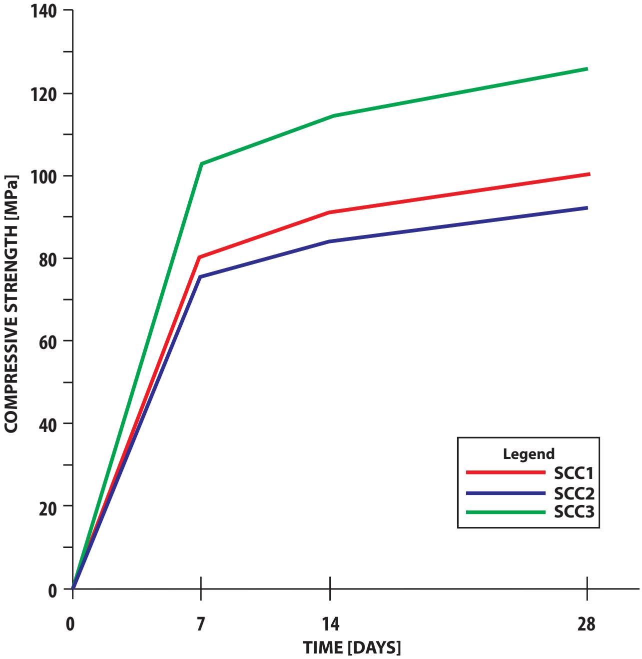

Fig. 5. Increase of the compressive strength of concrete

4. Conclusions

This paper presents an experimental investigation of the influence of the coarse aggregate shape of grains on the properties of fresh concrete mixture and hardened concrete on the example of high-performance, self-compacting concrete. The following conclusions may be drawn from the work presented in this paper:

1. By using properly selected aggregates, it is possible to obtain very high-performance, self-compacting concrete (compressive strength above 120MPa) with very favourable rheological parameters with regard to account slump flow and plastic viscosity;
2. The shape of the grain aggregate has a significant impact on the rheological parameters of fresh concrete. The best result can be achieved by using regular aggregate, the worst results were achieved with irregular coarse aggregates;
3. By appropriate selection of the shape of the grain aggregate, we can affect the rheological parameters of concrete;
4. By using regular aggregate, we can get a very high slump flow – this has been shown in studies. However, we very rarely need a mixture of self-compacting concrete with a slump flow value of 800mm. It is possible to reduce the water/binder ratio which will decrease the flowability and significantly increase the strength of self-compacting concrete;

5. Irregular coarse aggregate, due to its low strength, large area of grains and high friction angle compared to an regular aggregate and aggregate mix, should not be used for self-compacting concrete due to the relatively low strength parameters of the concrete and its low flowability.

Coarse aggregate is a significant proportion of the concrete volume and therefore has a serious impact on its quality. The appropriate choice of the type and quality of the aggregate is of significant importance for the quality of concrete. Coarse aggregate has a big impact on the consumption of cement to the concrete mix, workability, strength and durability of concrete [8]. Currently, there are technologies for the processing of aggregates capable of producing regular grains and appropriate coarse aggregate mixtures for the production of high-performance concrete. Given the results of this study, the author wishes to emphasise once more the benefits of a suitable aggregate in the production of high-performance, self-compacting concrete.

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