HIGH STRUCTURAL PERFORMANCES OF NON-CONVENTIONAL SELF-COMPACTING CONCRETE

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ABSTRACT: Self-compacting concrete, as a performing material whose casting and compacting can be made without applying the vibration technique, due to the flowability properties that allow it to flow by its own mass, was produced and tested in several versions of the material composition. Flowability gives high structural homogeneity and allows fast concrete pouring rate in a shorter time. During the experiment, four experimental versions were tested successively using coal ash, metallurgical slag, limestone dust as well as a combination of fly ash-slag as cementitious materials, that partially replaced Portland cement. Also, a water-reducing additive (polycarboxylate ether) was added in different ratios. Aggregates were chosen at low particle size (fine sand below 2 mm and granite gravel less than 12 mm). Mixing the materials together with the working water led to obtaining the paste with excellent flowability properties. The consolidated concrete had compactness and homogeneity and the mechanical characteristics were comparable to those of traditionally made concrete. Except for the remarkable flow characteristics of the paste, in this experiment it was proven that the compression strength of self-compacting concrete can reach very high values (after 28 days) of up to 60.4 MPa.

KEYWORDS: self-compacting concrete, flowability, paste, water-reducing additive, compression strength.

1. INTRODUCTION

The self-compacted concrete is a new solution in concrete technology due to the improvement of technical performances as well as working conditions. It has a large applicative domain, from light to strong structures. This innovative concrete is a future material type, due to its remarkable advantages.

It is a concrete that can flow by its mass, in totality fills the mold and allows complete compacting, including in difficult spaces. The component mixtures of this concrete have the mentioned attributes due to their excellent deformability, which allows them to keep the homogeneity in the fresh stage. The resistance to segregation and flowability of self-compacting concrete ensures high structural homogeneity, with few voids, satisfactory in-situ mechanical strength, and durability. It can be casted and compacted by its own mass without traditional vibrations and at the same time, it is powerful enough to be handled without applying traditional vibrations and simultaneously, it has adequate power to be handled without drainage or separation. The new concrete assures fast speed of casting in short time and easy flow into the mold. The strengthened concrete is dense and homogeneous having similar engineering features and durability compared to the traditional vibrated concrete [1, 2].

The self-compacting concrete started to be achieved only at the end of the 1980s in Japan and in Europe in the middle of the last decade of the 20th century, in Sweden in the field of road networks. At the beginning of the new millennium, designing and applying this concrete type experienced growing in the interest shown in a large part of European countries [1, 2].

There are known works of researchers from the Polytechnic Institute of Iasi (Romania) in the period 2010-2020 on the experimental production of some types of self-compacting concrete [3, 4]. Using mixtures containing ordinary Portland cement, pozzolanic additions (fly ash and silica fume), mineral filler (limestone), fine aggregate (up to 4 mm), and coarse aggregate (up to 16 mm), water, and a superplasticizer (polycarboxylate ether), self-compacting concrete specimens were made adopting the technique based on impact resonance as a substitute for traditional vibration. The workability tests of fresh concrete (slump flow test, T_{500}, V-funnel, and L-box) showed values comparable to those of similar vibrated concretes presented in the literature.

The use of coal ash in self-compacted concrete is an environmentally friendly variant and the excess heat of hydration is controlled during the making process. Fly ash contributes to improving permeability, durability, and homogeneity of concrete. Fly ash using is highly required to ensure a larger amount of powders necessary in the self-compacting concrete.

This type of concrete has the ability to self-compact, which eliminates one of the causes of discrepancy between the performances of specimens produced in laboratory conditions and those obtained under the conditions of fresh concrete on-site compaction. Also, self-compacting concrete requires less workforce than vibration-placing the conventional vibrated concrete.

According to [5], in general, self-compacting concrete mixtures have higher content of materials with low grain size, lower content of gravel as a coarse aggregate, low value of the highest dimension of great aggregate, high proportion of water-reducing additive as well as a larger volume of fresh concrete paste, compared to conventional vibrated concrete.

Regarding the mechanical features of self-compacted concrete, the opinions of many experts point to the idea that they are almost identical to those of vibration-processed concrete. However, there are quite a few conflicting opinions in the literature on this subject. Attiogbe et al. [6] came to the conclusion that the two types of concrete have similar modulus of elasticity. Other authors [7] consider that the elasticity modulus of self-compacting concrete is lower. The New Zealand Standard NZS 3106: 2009 notes that the tensile resistance of both concrete types is almost similar [5], although Marti-Vargas et al. [8] shows that the tensile resistance of self-compacting concrete is greater. The rupture modulus was measured by Leemann and Hoffmann [9] for both types of concrete and it is identical, while Turcry et al. [10] observed that the self-compacted concrete rupture modulus is higher. The explanation of these controversial results on mechanical characteristics of the two types could be due to several features of self-compacting concrete, according to Vilanova et al. [5], such as: changes in the mixture composition (high paste amount and fineness of materials), improving the material microstructure (lower porosity), and the lack of vibration during the pouring process.

Quantitatively, aggregates represent the largest part of the components of the concrete mix. They decisively contribute to the dimensional stability of the material. Previous experiments reported in the literature [5] confirmed that a rounded shape of the aggregate, under the conditions of a lower content of fine cement, is more adequate for obtaining the self-compatibility (through better flowability), compared to angular shape of the aggregate.

Another problem of aggregates is their inadequate dimensional gradation. Application of fillers (limestone or dolomite) has been proposed as a favourable solving. Also, coarse fly ash (fraction of over 45 μm) can contribute to improving the gradation of finer aggregates [5].

According to Ouchi et al. [11], there are some differences regarding the composition of mixtures for the manufacture of self-compacted concrete in Europe, Japan, and the United States. In Japan, the amount of ordinary Portland cement can vary between 220-530 $kg \cdot m^{-3}$, under the conditions of using fly ash (0-206 $kg \cdot m^{-3}$) and granulated slag (0-220 $kg \cdot m^{-3}$), as partial substitutes for cement. The fine/coarse aggregate ratio varies in three different versions: 751/789, 870/825, and 702/871 ($kg \cdot m^{-3}$). Water-reducing additive (between 4.4-10.6 $kg \cdot m^{-3}$) and viscosity modifying additive (between 0-4.1 $kg \cdot m^{-3}$) were other ingredients added to the mixture composition. The amount of water was within the limits of 165-175 $kg \cdot m^{-3}$. As a result, the slump-flow test indicated values between 600-660 mm. In Europe, the average amount of Portland cement is between 280-330 $kg \cdot m^{-3}$, being reduced by the addition of fly ash (190 $kg \cdot m^{-3}$), limestone powder as a filler (245 $kg \cdot m^{-3}$) or granulated blast furnace slag (200 $kg \cdot m^{-3}$), each in separate versions. The fine/coarse aggregate ratio is located within the following limits: 865/750, 870/750, and 700/750 ($kg \cdot m^{-3}$). Water-reducing additive varies between 4.2-6.5 $kg \cdot m^{-3}$, while viscosity modifying additive is used in a only version at 7.5 $kg \cdot m^{-3}$. The working water consumption is between 190-200 $kg \cdot m^{-3}$. The slump-flow test showed values within the limits of 600-750 mm. In the United States, ingredients used for manufacturing the self-compacting concrete included Portland cement in the range of 357-416 $kg \cdot m^{-3}$, the amounts of coal ash and granulated slag being quite low (45, and respectively, 119 $kg \cdot m^{-3}$). The fine/coarse aggregate ratio indicated a higher preference for fine aggregate, unlike the values used in Japan and Europe. The ratio of the mentioned aggregate types has the following values: 1052/616, 936/684, and 1015/892. Also, the water-reducing additive (in liquid form) is the favourite of American manufacturers, being used between 1602-2616 $ml \cdot m^{-3}$, while viscosity modifying additive (also, in liquid form) is used only in one of three versions at the value of 542 $ml \cdot m^{-3}$. The slump-flow test has values between 610-710 mm.

According to WRD Handbook [1], the curing is an important operation of all concretes, but especially for self-compacting concrete placed on a surface. The concrete layer tends to dry quickly, due to the larger amount of paste, the low ratio of water/fine materials as well as the loss of draining water on the surface. Thus, the concrete becomes more sensitive to cracking through plastic shrinkage, which increases by increasing the volume of fine materials in the composition. Therefore, the first stage of curing should be carried out immediately after placing and finishing the concrete to reduce the risk of shrinkage cracking due to early age moisture evaporation.

Rheology as the measuring science of deformation and flow is defined by the following parameters of fresh concrete: stability, mobility (or flowability), and compatibility of the material. Stability is the property by which the aggregate granules are maintained in a homogeneous distribution in the concrete matrix. The self-compacting concrete exhibits higher stability compared to traditional vibrated concrete. Mobility/flowability is the property of the fresh material to flow as a result of a mechanical impulse. The flow is influenced by the forces of cohesion, viscosity, and fractionation. Compatibility determines the compaction facility of fresh concrete, the expulsion of trapped air, and re-ordering aggregate granules in the hardened mass of concrete [1]. The choice of the concrete mixture composition is facilitated by knowing its rheological properties.

The main factors that influence rheological features of the self-compacting concrete are: material mixture ratios, consistency, hardening/stiffening, shape and maximum size of aggregate as well as admixtures.

The stability and filling capacity of self-compacting fresh state-concrete can be generally characterized by the following properties: flowability (measured by slump-flow test, using Abram's cone technique), viscosity (determined by V-funnel test), and passing ability (through L-box test) [1, 2] (see Figure 1). The main specific properties of self-compacting fresh state-concrete are flowability and stability due to the mixture peculiarities of this concrete type (higher paste volume, higher fine/coarse aggregate ratio, and less coarse aggregate by comparison with the peculiarities of traditional vibrated concrete).

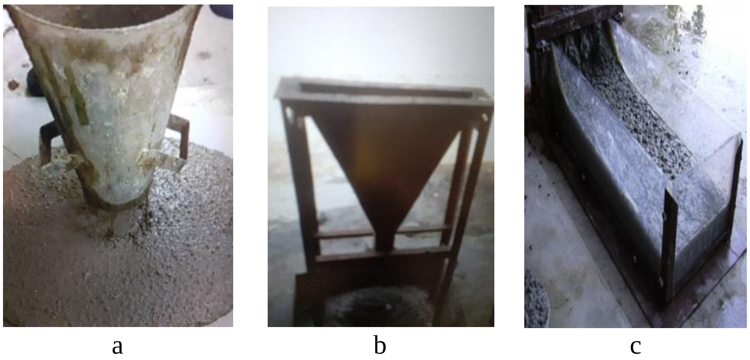

Figure 1. Equipment used for determining the main properties
a – slump-flow test; b – V-funnel test; c – L-box test.

As a conclusion of different experimental results, some contradictory, reported in the literature, a suitable correlation between parameters of mixture components and determining their value through specific measurements is required.

In the current paper, four experimental versions of the self-compacted concrete composition were tested, using coal ash and ground slag as suitable pozzolanic materials for the partial substitution of cement, limestone powder as a filler with similar properties, fine and coarse aggregates with low highest size of 10 mm, water-reducing additive, and working water. The purpose of adopting these compositional variants was to ensure excellent workability properties of the fresh material.

2. MATERIALS AND METHODS

2.1 Materials

The cementitious materials used in this experiment were ordinary Portland cement (CEM I type) and its partial replacement materials (coal ash, slag, and limestone). Class F-coal ash was provided 8 years ago from the Paroseni-Thermal Power Station (Romania) with an initial granulation under 200 µm, later reduced after grinding and sieving under 50 µm. Granulated blast furnace slag with grain dimensions between 2-6 mm was supplied by ArcelorMittal Galati (Romania) over two decades ago being preserved for using in several previous experiments. The slag grinding process allowed to obtain a fine powder with sizes less than 80 µm. Limestone ($Ca(OH)_2$) dust used as a filler in various building materials was commercially purchased with the medium particle size of 0.14 µm and the density of 2.6 $g \cdot cm^{-3}$ (originally from Vietnam). The oxide composition of class F-coal ash, slag, and limestone are shown in Table 1.

Quartz sand (98.8 %) with the particle dimension under 2 mm was chosen as a fine aggregate, while granite gravel (75 % SiO_2, 15.2 % Al_2O_3, 2.4 % Fe_2O_3, 1.6 % Na_2O) [12] with the maximum lump size below 10 mm, of which lumps below 6 mm were predominant (almost 80 %), was adopted as coarse aggregate.

Also, polycarboxylate ether (in form of powder) originally from India was chosen as a water-reducing additive.

The composition of the four self-compacting concrete versions is shown in Table 2.

Table 1. Oxide composition of coal ash, slag, and limestone (wt. %)

Composition	SiO_2	Al_2O_3	CaO	MgO	MnO	Fe_2O_3	Na_2O	K_2O
Class F-coal ash	48.1	26.4	3.6	3.2	-	8.6	6.0	4.1
Blast furnace slag	36.4	11.6	41.8	5.8	0.6	0.8	0.3	0.4
Limestone dust	8.2	1.5	71.4	1.3	-	1.0	0.1	0.6

Table 2. Composition of self-compacting concrete specimens

Composition	Version 1 ($kg \cdot m^{-3}$)	Version 2 ($kg \cdot m^{-3}$)	Version 3 ($kg \cdot m^{-3}$)	Version 4 ($kg \cdot m^{-3}$)
Portland cement (CEM I type)	280	320	390	270
Class F-coal ash	230	-	-	200
Ground granulated blast furnace slag	-	190	-	50
Limestone dust	-	-	170	-
Fine quartz sand aggregate (below 2 mm)	900	900	900	900
Coarse aggregate (granite gravel)				
- between 2-6 mm	360	360	360	360
- between 6-12 mm	350	350	350	350
Total	710	710	710	710
Polycarboxylate ether	4	5	8	7
Water	180	180	190	195

2.2 Methods

The manufacturing method of self-compacted concrete has as the main objective obtaining a mixture in fresh state having the capacity to flow under its own mass without using the traditional vibrating method of the material [11]. The essential difference between the method of choosing and preparing the components of mixtures used for manufacturing the self-compacting concrete and respectively, the concrete poured by traditional vibration methods. In principle, the flowability of the self-compacting concrete allows high structural homogeneity, the fresh material being able to be poured and compacted under its own mass. The high speed of concrete pouring allows the operation to be completed in a shorter time. The strengthened concrete is compact and structurally uniform with mechanical properties and durability comparable to those of traditional vibrated concrete.

Obtaining an adequate flowability is conditioned by the mechanical processing to a high fineness degree of replacing materials for Portland cement (coal ash, granulated slag) and the choice of limestone dust with extremely low sizes. The coarse aggregate is selected with rounded shapes and significantly lower grain sizes compared to those used in the case of traditional concrete. The ideal ratio between water and cement for making self-compacting concrete is recommended to be within the limits of 0.84-1.07 (by volume). Superior or inferior values of this range can produce trapping or segregating the fresh mixture [13].

After processing the mixture components that needed to reduce the grain size to the limits mentioned above, the mixing of fine materials (cement, coal ash, granulated slag, limestone dust, fine sand, and polycarboxylate ether) was carried out, including also the working water, in the amounts corresponding to each experimental version for 5 min. Then, coarse aggregate was introduced into the mix and stirring the materials has been continued for 5 min until the formation of the paste.

The typical procedure for hardening the fresh paste was performed by its pouring into cubic and rectangular metal molds for the curing process at 80 °C for 1 day. Then, the concrete samples were removed from the molds and stored for 7 and 28 days before determining the mechanical properties.

2.3 Investigation methods of self-compacted concrete specimens

Methods of investigating the characteristics of self-compacting concrete took into account both the freshly prepared concrete performances and those of the strengthened material. The workableness of freshly prepared concrete was analyzed by measuring the flowability using the slump-flow test applying Abram's cone method (ASTM C143-10), viscosity using V-funnel test, and passing capacity using L-box test. The concrete density was determined by Archimedes' method through the technique of water-intrusion (ASTM D792-20). Water-absorbing was measured by the immersion method of specimen under water (ASTM D570) after the storage time for 28 days-hardening. The compression strength of specimens was tested using EN 12390-3: 2001 standard. The tensile strength was analyzed applying EN 12390-6: 2023 and measuring the static modulus of elasticity was done according to ASTM C469-02e1. The microstructural appearance of self-compacting concrete specimens was investigated with the Biological Microscope model MT5000 with captured image, 1000 x magnification.

3. RESULTS AND DISCUSSION

3.1 Results

The first experimental results refer to the concrete characteristics in fresh state: flowability, viscosity, and passing ability measured with slump-flow based on Abram's cone method, V-funnel test, and L-box test. These results are shown in Table 3.

Table 3. Results of fresh concrete workability features

Feature	**Method**	**Version value**			
		1	2	3	4
Flowability (mm)	Slump-flow Abram's cone method	695	680	700	695
Viscosity (sec)	V-funnel test	9	10	8	10
Passing ability (h_1/h_2)	L-box test	0.91	0.90	0.93	0.92

According to the data in Table 3, flowability of the fresh concrete specimens falls within the range of valid acceptance criteria for self-compacted concrete (between 650-800 mm) mentioned in [1]. Consulting the Table 2, versions 3, 1, and 4 have the best flowability characteristics, whose compositions include (except for Portland cement) limestone dust (version 3), fly ash (version 1), and the fly ash-slag combination with fly ash predominant content (version 4). On the other hand, version 3 used the largest amount of polycarboxylate ether (8 $kg \cdot m^{-3}$), instead between the amounts introduced in versions 4 and 1 there is a significant difference in favour of version 4 (7 compared to only 4 $kg \cdot m^{-3}$). Viscosity of the fresh concrete measured through V-funnel test showed constancy of flow time values (between 8-10 sec) in the four experimental versions, falling within the acceptance criteria for self-compacting concrete in the range of 6-12 sec. Similarly, the passing capacity of the experimentally made fresh self-compacted concrete indicated acceptable values of the measured levels h1/h2 between 0.90-0.93 using L-box test, for all versions tested.

The second stage of measurements carried out in this experiment referred to the mechanical and physical characteristics of self-compacted concrete determined after the usual curing process of fresh concrete followed by the storage of specimens removed from the molds for 7 and 28 days. The concrete density, water-absorbing capacity, compression resistance, tensile resistance, elasticity modulus have been investigated as well as the microstructural appearance of the four concrete specimens. Results of these determinations are presented in Table 4.

Table 4. Physical and mechanical features of concrete specimens

Characteristic	**Version 1**	**Version 2**	**Version 3**	**Version 4**
Concrete density after 28 days ($kg \cdot m^{-3}$)	2342	2360	2340	2356
Water-absorbing capacity (vol. %)	0.83	0.91	0.85	0.86
Compression resistance (MPa)				

- after 7 days	34.1	36.2	33.8	34.5
- after 28 days	59.8	60.4	58.9	59.3
Tensile resistance (MPa)				
- after 7 days	2.0	2.2	2.0	2.3
- after 28 days	3.9	4.1	4.0	4.3
Modulus of elasticity (GPa)	35.2	34.8	34.5	36.0

The analysis of results in Table 4 indicates excellent values of the compression resistance both after 7 days of storage, but especially after 28 days, reaching a level within the limits of 58.9-60.4 MPa. Tensile resistance measured after 7 and 28 days falls within the limits of average values compared to traditional concrete poured by vibration. After 28 days, self-compacted concrete exceeded the value of 4 MPa for tensile resistance. The modulus of elasticity with values between 34.5-36.0 GPa is generally lower compared to traditional vibrated concrete with relatively similar compression resistances. The properties that are mainly influenced by the water/binder ratio such as compression and flexural strength were found to be relatively similar in the case of self-compacted concrete and conventional vibration-placed concrete, according also to conclusions of Leemann and Hoffmann [9]. Generally, investigating mechanical properties of self-compacting concrete making in this experiment has confirmed that these can be considered similar with those of conventional vibration-placed concrete, despite some contradictory opinions of specialists in this field.

Appearance of self-compacting concrete specimens made in the four experimental versions is presented in Figure 2. These specimens have been subjected to the curing process at 80 °C for 24 hours and then have been stored for 28 days.

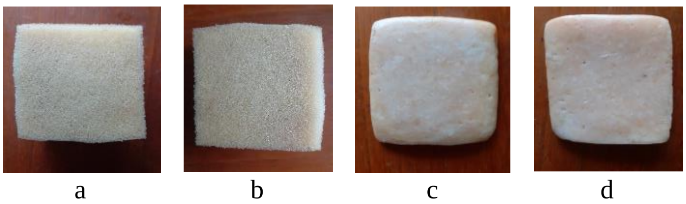
a b c d

Figure 2. Aspect of self-compacting concrete samples
a – version 1; b – version 2; c – version 3; d – version 4.

The main characteristic of specimen surfaces is compactivity and homogeneous as a result of excellent flowability properties of all these specimens, regardless of the tested manufacturing recipe.

Instead, major differences are observable in the pictures representing the microstructural appearance of specimens (Figure 3) and are mainly due to the various sorts of cementitious raw materials added to the mixture as a partial substitute for the traditional cement.

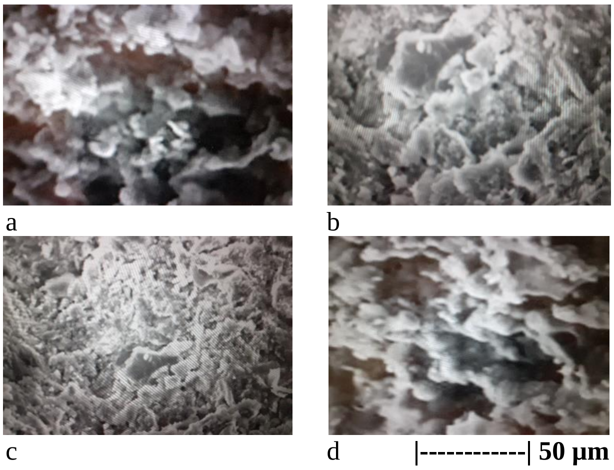

Figure 3. Microstructural appearance of self-compacting concrete samples
a – version 1; b – version 2; c – version 3; d – version 4.

Version 3 including very fine limestone dust and also the highest amount of water-reducing additive (polycarboxylate ether) seems to be the finest microstructure among the four specimens, while versions 1 and 4 consisting only of cement and coal ash and respectively, cement, coal ash, and partially ground granulated slag, have less fine microstructure.

3.2 Discussion

Although self-compacted concrete may be manufactured with the same material types in the mix as in the case of traditional concrete, ensuring remarkable features of flowability requires several specific rules regarding the proportions and dimensions of the mix components. Thus, they are required higher powder content, reduced amount and grain size of coarse aggregate, more important intake of superplasticizer, optimal correlation between fluidity, deformability, filling capacity as well as separation resistance. Due to the properties of flowability, compatibility, and passing ability, the self-compacted concrete represents an interesting option for the construction sector.

In the current work, secondary products such as coal ash and granulated slag from the energy and metallurgical industry were used. Their application in manufacturing process of self-compacted concrete as partial substitutes for Portland cement is an environmentally friendly method reducing important emissions of greenhouse gases (specific to the manufacture of Portland cement). Fly ash, by its presence into the mix, contributes to growing the ratio of materials in powder state. Also, the utilization of coal ash, like limestone filler in the self-compacting material facilitates the formation of a low-porosity material. The denser macrostructure contributes for a lower plastic settlement [1].

4. CONCLUSION

The work aimed at the production of a self-compacting concrete, a modern construction material with excellent flowability properties, flowing under its own weight when poured. Except for Portland cement used as the main raw material, coal ash, slag, limestone and coal ash/slag combination in a weight ratio of 4:1, were successively tested as materials for partial substitution of cement. The mixture was completed with polycarboxylate ether as a water-reducing additive and water for the formation of the paste. Testing its characteristics through usual methods highlighted obtaining very good results on flowability (between 680-700 mm), viscosity (in the range of 8-10 sec), and passing ability (within the limits of 0.90-0.93), the best of them being attributed to the version using limestone dust together with the cement and the highest amount of additive. Determining mechanical and physical characteristics of hardened concrete after the curing process at 80 °C for 24 hours and storing specimens for 7 and 28 days showed excellent values of compression strength, especially after 28 days, the highest level (60.4 MPa) being reached in the case of version using slag together with the cement and a lower amount of water-reducing additive. The other physical and mechanical features (density, water-absorbing capacity, tensile resistance, and elasticity modulus) had values of average level compared to conventional vibrated concrete.

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