STUDIUL COMPARATIV AL PROPRIETĂȚILOR BETONULUI AUTOCOMPACTANT ȘI BETONULUI VIBRAT INCLUZÂND CURBA CARACTERISTICĂ COMPLETĂ LA COMPRESIUNE

THE COMPARATIVE STUDY OF THE SELF-COMPACTING CONCRETE AND OF VIBRATED CONCRETE PROPERTIES INCLUDING THE COMPLETE CHARACTERISTIC CURVE UNDER COMPRESSION

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The self-compacting concrete (SCC) can be promoted in construction industry only after performing a wide range of studies upon its properties. The mechanical characteristics of this material have been less analysed, the up-to-date results from the scientific literature often being in contradiction. The study of the SCC behaviour in the post-elastic range, which is an important feature in the structural design of the constructions located in seismic areas, provides the possibility to evaluate the real energy dissipation capacity. Within this paper, a comparative study between the essential properties and the complete stress-strain curves of the (SCC) and vibrated concrete (VC) loaded in compression has been performed. The experimental program has been carried out using an innovative testing system conceived and patented at the Faculty of Civil Engineering and Building Services from the "Gheorghe Asachi" Technical University of Iasi. The analysed concrete mixes have been prepared in three batches keeping constant the amount of cement, and the concrete flowability was achieved through variation of the limestone filler and concrete admixtures quantities. The mechanical characteristics of both self-compacting concrete and vibrated concrete are different. This difference becomes more obvious once the volumetric fractions of coarse and fine aggregates are modified. It can be also stated that the complete stress-strain curves of SCC and VC are different revealing the convenient capacity of SCC to absorb deformation energy.

Promovarea betonului autocompactant (BAC) în industria construcțiilor, poate fi realizată doar după efectuarea unor studii cuprinzătoare ale proprietăților acestuia. Caracteristicile mecanice ale acestui material au fost mai puțin analizate, rezultatele comunicate până în prezent în literatura de specialitate fiind deseori contradictorii. Studiul comportării BAC în domeniul postelastic, caracteristică importantă pentru proiectarea structurilor de construcții amplasate în zone seismice, asigură posibilitatea de a evalua capacitatea reală de disipare a energiei de deformare. În cadrul acestei lucrări a fost efectuat un studiu comparativ privind proprietățile principale și curbele caracteristice complete ale betonului autocompactant (BAC) și betonului vibrat (BV) la solicitarea de compresiune centrică. Programul experimental s-a efectuat utilizând un sistem de testare conceput și brevetat la Facultatea de Construcții și Instalații din cadrul Universității Tehnice "Gheorghe Asachi" din Iași. Rețetele de beton analizate au fost realizate în trei serii, cu menținerea constantă a cantității de ciment, iar fluiditatea BAC fiind ajustată din variația adaosurilor de filer de calcar și a aditivilor superplastifianți. Proprietățile mecanice ale BAC diferă de cele ale BV mai ales în situația în care se modifică fracțiunile volumetrice ale agregatelor. De asemenea, curbele caracteristice complete ale celor două tipuri de beton diferă reliefând capacitatea de absorbție convenabilă a energiei de deformare de către BAC.

Keywords: *self-compacting concrete, workability, post-elastic domain, complete stress-strain curve, energy dissipation capacity*

1. Introduction

The self-compacting concrete (SCC) is an innovative material in construction industry and it was worldwide promoted at the end of 20th century [1]. Its main characteristic is the workability provided by the flowability of fresh concrete and by the ability of eliminating the entrapped air under its own weight, without any other external action [2]. The increased filling ability, the passing ability – the ability of SCC to flow through tight openings, even in the presence of dense reinforcement, the ability of maintaining its stability and homogeneity in fresh state, are among the main features that recommend the use of SCC in Civil Engineering applications [3, 4]. The improved performance of this new material is due to an appropriate use of each constituent material and due to the newly conceived mix design methods that imply an adjustment of the coarse aggregate, fine aggregate and admixtures content [5, 6].

The main advantages of self-compacting concrete are: the enhanced quality of the structural elements, the moderate need of skilled workers for

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concrete placement, the faster construction time etc. [7]. The SCC testing methods have been developed after its occurrence and they are continuously improved. The mechanical characteristics are still insufficiently investigated, the research results obtained so far are not harmonized, and the studies related to the material behaviour in the post elastic range are quite rare, the usual laboratory tests being frequently limited to the determination of the maximum load carrying capacity [8].

The structural design of constructions subjected to seismic action needs to consider not only the appropriate mechanical strength of the structural elements, but also their adequate level of ductility in order to obtain a large post-elastic deformation capacity [9]. Under these circumstances, it is necessary to know the post-peak behaviour of the constituent materials of the structural elements.

In the case of reinforced concrete structures, ductility can be assessed using the complete stress-strain curves of steel and concrete. Usually, the characteristic curve of concrete for the post-peak range is only estimated, without knowing the real behaviour of the material. The stress-strain curve cannot be plotted also for the post-elastic domain due to the sudden failure of concrete specimens produced when the ultimate stress is reached and the entire amount of strain energy stored by the testing machine is shortly released [8].

In order to plot the complete stress-strain curve of concrete loaded in compression, special displacement or strain controlled testing machines are needed. The experimental program described in this paper has been carried out utilising an innovative testing system conceived and patented by a research team from the Faculty of Civil Engineering and Building Services Iasi [10].

Within this paper, a comparative study between the energy dissipation capacity of the self-compacting concrete (SCC) and of the vibrated concrete (VC) has been performed, based on the complete stress-strain curves experimentally determined.

2. Concrete mixes

2.1.Materials

The concrete mixes analysed within this paper are based on the same concrete grade and they have been adjusted for the purpose of the current experimental program.

The cement used for the considered concrete mixes was CEM II/A-LL 42.5R [11]. This material is recommended for the execution of structural and non-structural cast in place or precast construction elements, repairing works, fillings, coatings, special floor screeds and mortars, being characterised by a high early strength which facilitates a rapid execution time, even in cold weather conditions (<5^{0}C). The Portland limestone cement CEM II/A-LL 42.5R contains 80÷94% of clinker, 6÷20% of limestone filler, which restrains the concrete bleeding ensuring at the same time an improved hydration of the cement, and 0÷5% of other minor additional constituents. The limestone addition has a minimum content of 75% by mass of calcium carbonate ($CaCO_3$), the amount of clay is less than 1.20 g/100 g and that of total organic carbon (TOC) is less than 0.20% by mass.

The aggregates have been provided by Moțca sand and gravel plant from Iasi County. They were previously washed and sorted by the supplier in three fractions: 0-4 mm; 4-8 mm and 8-16 mm.

The limestone filler used in SCC composition as mineral addition contributes to an increasing of the paste volume. This way, the use of the viscosity modifying admixtures (VMA) can be avoided. At the same time, the limestone filler improves the workability of fresh concrete.

The superplasticisers lately used for concrete production are polycarboxylate-ether based admixtures (PCEs). They contribute to a reduction of the mixing water content up to 20% and are also known as high-range water reducers (HRWR) [12].The amount of admixtures in regular concrete mixes represents 0.5% by the cement quantity, but in the case of SCC it was established through a series of successive laboratory tests.

2.2. Design of concrete mixes

The design of concrete mixes (Table 1) has been governed by the following aspects:

- The cement amount has been maintained constant for all the three mixes corresponding to one batch;
- The SCC flowability has been achieved due to an increase of the paste volume obtained through the use of mineral addition (limestone filler). The limestone filler has also provided the required viscosity to the mix;
- The volumetric fraction of sand used for the SCC preparation has been selected the same for all the three batches. For the first proposed mixes (SCC1, SCC2, SCC3), the amount of sand represented 48% from the total aggregate volume, and for the second proposed mixes (SCC1-A, SCC2-A, SCC3-A), the amount of sand represented 50% from the total aggregate volume.
- The SCC mix fluidity has been enhanced through the use of superplasticiser (HRWR);
- To obtain reliable results it was proposed to design some fluid concrete mixes that are also suited for pumping and frequently used in construction industry.

Table 1

Mix proportions/ *Reţete de beton*

Concrete mix/ *Reţeta de beton*	Cement/ *Ciment*	Aggregate/ *Agregat*	Sand/ *Nisip*	Limestone filler/ *Filer de calcar*	Water/Cement ratio (W/C)/ *Raport apă/ciment*	High-range water reducer (HRWR)/ *Superplastifiant*
	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	-	[l/m^3]
1st batch						
VC1	320	1105	799	-	0.50	1.6
SCC1	320	881	814	160	0.53	4.5
SCC1-A	320	883	883	150	0.50	4.8
2nd batch						
VC2	340	1112	756	-	0.50	1.7
SCC2	340	876	809	150	0.53	5.1
SCC2-A	340	876	876	140	0.50	5.4
3rd batch						
VC3	360	1082	739	-	0.50	1.8
SCC3	360	876	809	130	0.53	5.1
SCC3-A	360	853	853	120	0.50	5.8

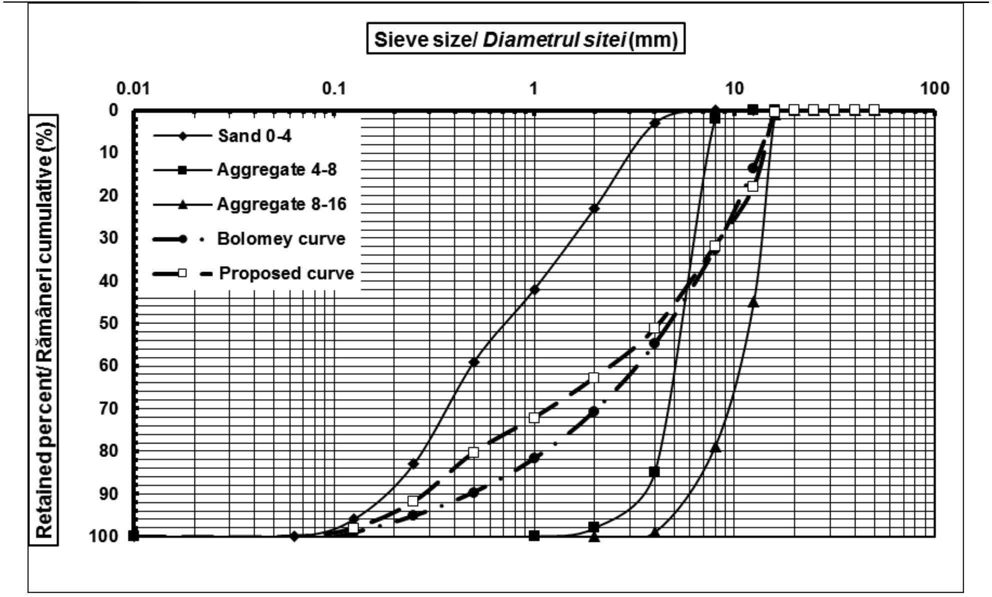


Fig. 1 - Aggregates grading curves / *Curbele granulometrice ale agregatelor.*

The aggregates grading curves have been determined in accordance with EN 12620: 2013 [13] specifications and are represented in Figure 1.

The main volumetric and quantitative characteristics of the prepared SCC mixes and their correlation with the guidelines and

Table 2

The correlation between the composition of SCC mixes and the international requirements/ *Corelarea dintre reţetele de beton autocompactant (BAC) şi prevederile internaţionale*

Material	Units of measure / *Unităţi de măsură*	Concrete mix/ *Reţeta de beton*							
		SCC1	SCC 1-A	SCC 2	SCC 2-A	SCC 3	SCC 3-A	The European Guidelines for SCC [4]	ACI 237 [14]
Powder	kg/m^3	480	470	490	480	490	480	380-600	>458
	l/m^3	165	161	160	164	166	162	-	-
Paste	l/m^3	359	346	373	359	381	368	300-380	340-400
Water	l/m^3	170	160	180	170	190	180	150-210	-
Coarse aggregate	kg/m^3	881	883	876	876	883	809	750-1000	-
	l/m^3	333	327	327	316	327	316	270-360	280-320
Fine aggregate	kg/m^3	814	883	809	876	883	809	-	-
	% G_{ag}*	48	50	48	50	50	48	48-55	-
Water/Powder ratio by volume	kg/m^3	0.35	0.34	0.38	0.35	0.34	0.38	-	0.32-0.45
	l/m^3	1.03	0.99	1.01	1.04	1.1	1.1	0.85-1.10	-

*percentage of total aggregate weight

specifications proposed by the representative European and American concrete research centres the European Precast Concrete Organisation (BIMB), the European Cement Association (CEMBUREAU), the European Ready-mix Concrete Organisation (ERMCO), the European Federation of Concrete Admixture Associations (EFCA), the European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) and the American Concrete Institute (ACI) [4, 14] are indicated in Table 2.

The same mixing process - the free-fall vertical mixing - has been used for all batches in order to ensure similar preparing conditions and it was carried out until a homogeneous mix, with no segregation or bleeding, was achieved. For the SCC mixes, the constituent materials were added to the mix as it follows: the aggregates have been first added to the mixer, followed by the cement and the limestone filler; this was immediately followed by 75% of the mixing water and the superplasticisers; the other admixtures have been added in the end with the rest of water.

3. Properties of self-compacting concrete

3.1. Properties in fresh state

The current standardised testing methods [15-17] used to assess the properties of self-compacting concrete in fresh state are based on the EN12350 specifications for regular concrete. According to these standards and to *The European Guidelines for Self-Compacting Concrete* [4], the SCC in fresh state is characterised by four important features: flowability, viscosity, passing ability and segregation.

Within this paper the following tests have been carried out for the considered self-compacting concrete mixes:

The slump-flow test and t_{500} time. The result of the slump-flow test is an indication of filling ability of SCC and t_{500} time is a measure for the flow rate and an indication of the relative viscosity [15]. Also a visual inspection during this test enables to appreciate the segregation resistance of SCC [18, 19] (Figure 2.a). The differences between the measured diameters (the maximum diameter and the perpendicular one) have been less than 30mm. It corresponds to the allowable standard limit [15] and it means that all the tested concrete mixes have the necessary flowability. The obtained results are given in Table 3. According to *The European Guidelines for Self-Compacting Concrete* [4], the values of slump-flow (SF) in millimetres, between 660mm and 750mm, indicate *the consistence class SF2*, and the values of t_{500} time in seconds greater than 2s indicate *the viscosity class VS2* for all the SCC mixes.

V-funnel test. This test is used to assess the viscosity and the filling ability of SCC (Figure 2.b). During this test all the concrete mixes have passed through the bottom gate without creating any blocking during flowing. According to the recorded flowing time, between 9s and 25s, all the concrete mixes have *the viscosity class VF2* [4, 16].

L-box test. This testing procedure is used to determine the passing ability ratio of SCC (Figure 2.c). This represents the ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation and without creating any blocking [17]. The three bars test, which simulates a denser reinforcement, has been carried out. The passing ability ratio (PL) determined for all the tested mixes was greater than 0.8 and according to [4] they are within *the passing ability class PA2*.

All the testing procedures are shown in Figure 2 and the results are summarised in Table 3.

A comparison between the properties of regular vibrated concrete (VC) and of self-compacting concrete (SCC) in fresh state it is not possible since the testing procedures are different. However it is obvious that the SCC workability is clearly superior to that of VC.


a) b) c)

Fig. 2 – SCC testing in fresh state/ *Testarea BAC în stare proaspătă*
a) The slump flow test/ *Testarea lucrabilității*; b) V-funnel test/ *Testul cu pâlnia V*; c) L-box test/ *Testul cu cutia L*

Table 3

SCC tests results in fresh state/ *Rezultatele testării BAC în stare proaspătă*

Concrete mix/ *Reţeta de beton*	Slump-flow test [mm]	t_{500} time [s]	V-funnel test [s]	L-box test
SCC1	680	4.2	14.4	0.84
SCC 1-A	665	4.3	15.1	0.85
SCC 2	690	4.1	11.3	0.88
SCC 2-A	710	3.5	9.4	0.94
SCC 3	720	2.9	9.2	0.93
SCC 3-A	700	2.5	9.8	0.91

3.2. Properties in hardened state

The regular concrete placement into the moulds has been gradually done in three layers and their compaction was achieved with a vibrating table. In the case of SCC, the mix has been poured into the moulds from an appropriate distance that ensures the elimination of the entrapped air without any mechanical compaction process. After 24h, the specimens have been demoulded and stored for 28 days into the climatic chamber, where a moisture content of about 95±5% and a temperature of 20ºC were provided.

3.2.1. Compressive strength of self-compacting concrete

The compressive strength of concrete determined experimentally is influenced by the following factors: the composition and properties of the constituent materials, their storage conditions and the testing conditions.

The failure mechanism of the concrete specimens loaded in compression depends on the structural characteristics and on the progressive way of failure under maximum stresses. The occurred cracks develop around the aggregates or around the voids from the hardened cement which are working as some obstacles for cracks propagation. In case of high-strength concrete, due the increased strength of the hardened concrete, the cracks pattern propagates also through the aggregates [20].

The structural configuration of the real reinforced concrete members is generally different from the cubical shape and the compressive strength of cubical concrete specimens cannot define the real behaviour of the structural elements subjected to compression. Under these circumstances, the compressive strength of cubical concrete specimens is not used in structural design, being utilised to establish the concrete grade. The main performance indicator for the design of the structural members is the compressive strength of cylindrical concrete specimens $f_{c,cil}$. This represents the ultimate stress obtained at the age of 28 days on concrete cylinders subjected to uniaxial compressive load [21].

Within the experimental program carried out for the purpose of this paper, the cylindrical compressive strength has been determined in accordance with SR EN 12390-3:2009 requirements [22]. Using a universal testing machine, Zwick/Roell, the specimens have been tested at a constant rate of loading of 0.4 MPa/s until failure. A number of twenty specimens from each concrete mix of the three batches, previously detailed in Table 1, have been tested. The average values of the obtained results are shown in Figure 3, and the failure modes are illustrated in Figure 4.

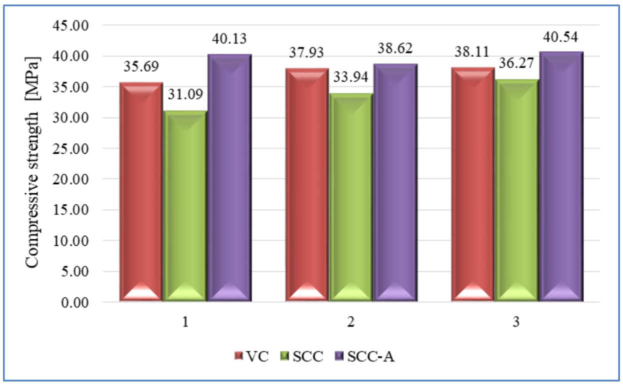


Fig. 3 – Compressive strength of cylindrical concrete specimens (VC vs SCC)/ *Rezistența betonului la compresiune determinată pe probe cilindrice (BV vs BAC).*

For the first concrete batch, the compressive strength of self-compacting concrete SCC1 was lower than that of vibrated concrete VC1 with 12.9%, while for the self-compacting concrete SCC1-A an increase of 12.4% with respect to compressive strength of VC1 was recorded. For the second batch, the same tendency was observed. The compressive strength of vibrated concrete VC2 was greater than that of self-compacting concrete SCC2 with 10.5% and lower than that of self-compacting concrete SCC2-A with 1.8%. For the last batch, the highest values have been recorded. A difference of 4.8% between the compressive strength of vibrated concrete VC3 and of self-compacting concrete SCC3 was observed, and an increase of 6.4% with respect to VC3 was obtained for the compressive strength of self-compacting concrete SCC3-A.

Based on these results, it can be stated that the differences in terms of compressive strength between these two materials, vibrated concrete (VC) and self-compacting concrete (SCC), are signifycantly reduced once the cement content is increased and the limestone filler content is decreased in the designed concrete mixes. Even if the limestone filler is considered an inert material, its addition into the self-compacting concrete will help to maintain its stability in fresh state and to obtain a denser material in hardened state. At the same time, the use of an amount of limestone filler greater than 30% from the cement quantity diminishes the compressive strength of concrete. This fact is confirmed by the results obtained on the two types of SCC from one batch.

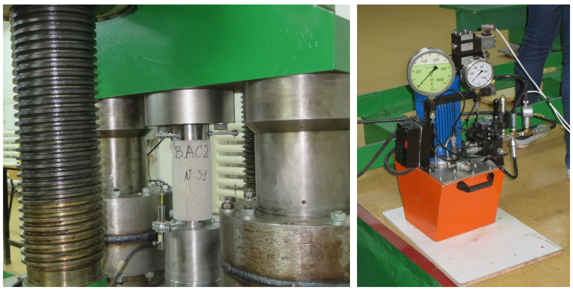
Fig. 4 – Failure of the cylindrical concrete specimens loaded in compression/ *Cedarea probelor cilindrice din beton la compresiune.*

3.2.2. The complete stress-strain curve of self-compacting concrete under compression

The complexity of determining the complete characteristic curve of concrete loaded in compression rise up from the fact that the strain energy stored into the common testing systems is suddenly released when the concrete specimens are broken [23]. As a consequence of this phenomenon the loading rate, which is a fundamental parameter for any experimental testing, is essentially modified influencing the final response of the specimens [24].

The experimental program, which aims to determine the complete stress-strain curves for the materials proposed and analysed within this paper has been carried out using a testing system developed and patented at the Faculty of Civil Engineering and Building Services from ”Gheorghe Asachi” Technical University of Iasi, following the procedure already described in a previous paper of some of the authors [8]. This system has been achieved by introducing an additional device able to substitute the loss of carrying capacity of the specimens, thus preventing the instability phenomena caused by the failure of the concrete specimens [10]. The mechanical device attached to the universal testing machine is represented by two hydraulic cylinders (Figure 5.a) to which a load almost equal to the maximum capacity of the testing machine is applied [25, 26]. After reaching the equilibrium state of the testing machine, the concrete specimen equipped with a loading cell and displacement transducers (LVDTs) is centred between the two cylinders.

The most important factor during this type of experimental testing is to maintain the strain rate to a constant value [27]. This is done by means of a valve which gradually releases the oil from the two hydraulic cylinders (Figure 5.b). Therefore, the test evolves continuously, the two additional cylinders take over the applied load and they will progressively transfer it to the concrete specimen so that to prevent the sudden release of the strain energy stored within the system [8].



a) b)

Fig. 5 - The device used to determine the complete stress-strain curve/ *Dispozitivul de determinare a curbei caracteristice complete a)* hydraulic cylinders/ *cilindri hidraulici; b)* hydraulic device/ *dispozitiv hidraulic*

The concrete cylinders, having the dimensions of 100mm by 200mm (diameter x height), have been previously machined at their top and bottom sides to eliminate the friction influence between the specimen and the testing machine plates, upon the recorded results, Figure 6.

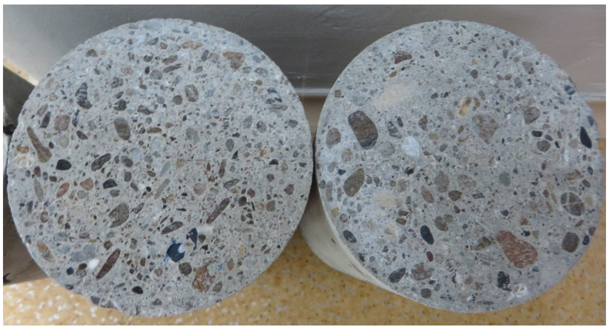


Fig. 6 - The specimens end surfaces machining for a perfect contact with loading plates of the testing machine/ *Prelucrarea mecanică a capetelor probelor pentru un contact perfect cu platanele mașinii de încercat.*

In order to ensure a highly accurate data recording, three LVDTs have been placed on the circumference of the testing machine plates at 120°, Figure 7a.

The complete stress-strain curves determined during the current research work have been obtained by testing three cylindrical specimens from each concrete mix and the results are summarised in Figure 8.

Analysing these curves it can be observed that the axial strain corresponding to the maximum

a) b)

Fig. 7 - Establishing the complete characteristic curve of concrete loaded in compression/ *Determinarea curbei caracteristice complete a betonului la compresiune:a)* the LVDTs connection on the cylindrical specimen/ *fixarea traductorilor pe proba cilindrică;* b) the specimen features after testing/ *aspectul probei după realizarea testului.*

stress is almost the same both for the vibrated concrete mixes VC1 and VC2, and for the self-compacting concrete mixes SCC1 and SCC2. Regarding the ultimate strain, the value was recorded when the normal stress reached 10% from the maximum stress on the descending side of the complete characteristic curves [8].

In case of first concrete batch, the largest value of recorded strain energy was for vibrated concrete (VC1), the difference related to SCC1 being of 11.7% and related to SCC1-A of 3.3%. This phenomenon occurs due to the larger difference between the volumetric fractions of coarse and fine aggregates.

According to the results obtained for the second concrete batch, the regular vibrated concrete (VC2) has an ultimate strain less by 2.5% compared to SCC2-A, and greater than SCC2 by 4.8%.

The post-peak strain energy recorded for the third concrete batch indicated larger values for SCC3-A, the increasing being of 1.8% with respect to VC3.

4. Conclusions

The final appearance of self-compacting concrete in hardened state is different from that of vibrated concrete due to the changes performed upon the regular concrete mix. Usually, the SCC mixes are designed considering a lower water/ cement ratio, a higher paste volume while the aggregates are carefully selected based on their shape and dimensions. All these measures are mandatory in order to obtain the required classes of workability, homogeneity and segregation resistance of fresh mixes. The decrease of water content implies a reduction of concrete porosity and of the distance between the cement particles. This way creates a favourable situation to obtain a material with an increased degree of compaction in hardened state.

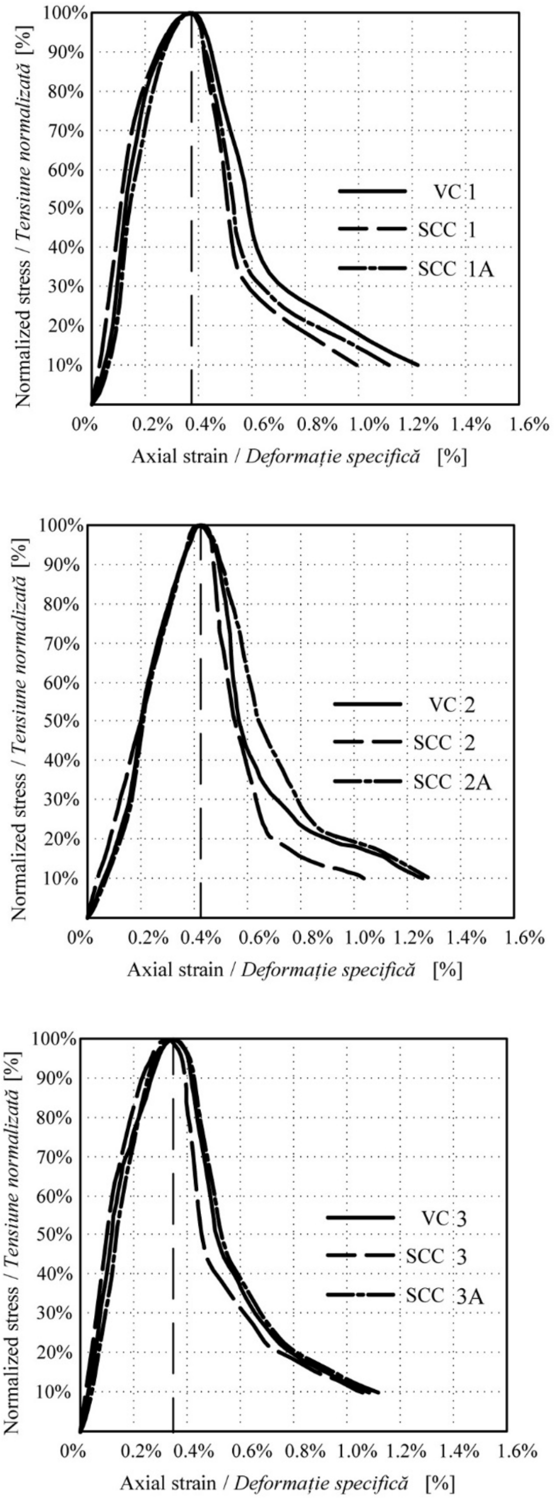


Fig. 8 - The stress-strain normalized curves/ *Curbele caracteristice complete normalizate* .

In case of SCC, the quantity of extra water remained after the hydration process is less than that resulted in case of VC. Consequently, there is a reduction of the grids of interconnected pores in hardened state. The use of superplasticizers and of mineral admixtures finally creates a denser matrix with an improved adherence between the aggregates and the cement paste, but also with a more uniform stress distribution.

The mechanical characteristics of both self-compacting concrete and vibrated concrete are different, taking into account that they are based on the same initial concrete grade and the cement quantity has been maintained constant for all the concrete mixes within one batch. This difference is even more obvious once the volumetric fractions of coarse and fine aggregates are modified.

The self-compacting concrete mixes require some restrains regarding the dosage of fine and coarse aggregate in order to correspond to the conformity criteria established by *The European Guidelines for Self-Compacting Concrete.*

For the self-compacting concrete mixes SCC1, SCC2 and SCC3, with the amount of sand representing 48% from the total aggregate volume and with a bigger addition of limestone filler, the lowest values for the compressive strength of cylindrical concrete specimens $f_{c,cil}$ have been recorded.

The same tendency was observed also in terms of energy dissipation capacity. Compared with results obtained for the vibrated concrete mixes (VC1, VC2 and VC3), the energy dissipation capacity recorded for the self-compacting concrete mixes, SCC1, SCC2 and SCC3 has been reduced with 11.7%, 4.8% and respectively 2.7%. These differences are diminished once the powder quantity decreases.

For the second proposed mixes SCC1-A, SCC2-A and SCC3-A, with the amount of sand representing 50% from the total aggregate volume, a decreasing tendency of the energy dissipation capacity with 3.3% related to the vibrated concrete in case of the first batch has been observed. In case of the next two batches, the energy dissipation capacity gained an improvement of 3.1% and 1.8% for the SCC-A mixes compared to VC mixes.

Based on these concluding remarks, it can be stated that the complete stress-strain curves of SCC and VC are significantly different.

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