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STATIC AND DYNAMIC CHARACTERISTICS OF WASTE CERAMIC AGGREGATE FIBRE REINFORCED CONCRETE

Abstract

There are multiple obstacles associated both with technology and properties of waste ceramic aggregate concrete preventing its wide production and application. In the research programme these limitations were addressed through utilizing steel fibre reinforcement and the phenomenon of internal curing. After laboratory tests of mechanical properties a numerical analysis of composites in question was conducted.

Keywords

Concrete, fibre, waste, aggregate, recycling, sustainable, experimental tests, FEA.

1 INTRODUCTION

Brittle cement composites entered civil and structural engineering at the end of 19th century. For the last 150 years different types of concretes and mortars have become the most commonly applied construction materials in the world. Aggregate is the main component of any cement composite. It covers from 60 % to 80 % of concrete volume. Currently, the worldwide annual production of cement composites consumes over 20 billion tonne of aggregate. It means that mankind consumption of aggregate reached 3 tonne per person per year [1]. So far the main research effort associated with the environmental aspects of the production and use of cement and concrete was focused on cement. During this rush to make cement greener the importance of an aggregate has been almost forgotten.

During the production of commonly harnessed (in civil and structural engineering) ordinary concrete the weight proportion of consumed coarse and fine aggregate is approximately equal to 3:1 [2]. In a given geographical location natural resources of fine and coarse aggregate are rarely available in this very needed proportion [3]. Natural availability of mineral aggregate causes inefficient and unbalanced use of existing resources, which considerably influences natural environment. Waste ceramic aggregate (WCA) can be an answer to this problem of growing importance. Utilizing WCA in concrete production can solve two urgent ecological issues at the same

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time. Firstly, it would enable utilisation of large volumes of construction/demolition waste. Secondly, it would provide locally available coarse aggregate in areas where it is in constant demand [4]. The growing research effort to successfully harness ceramic waste in construction industry [5] resulted in successful applications of WCA in concrete elements characterized by less demanding mechanical properties (e.g. pavement slabs) [6]. Utilizing WCA as a substitute of traditional aggregate is technologically quite demanding. The main problems are associated with workability of a fresh mix. High water absorptivity of WCA makes preparation of a workable mix very tricky. Conventional concrete mix designing methods are almost useless in this case. Exchanging ordinary coarse aggregates by WCA significantly influences the homogeneity of mechanical properties of cast concrete. Mechanical properties are characterized by lesser values in comparison to ordinary concrete and the populations of results themselves are characterized by significantly higher standard deviations. In order to evade these "performance" issues the authors decided to reinforce WCA concrete by engineered steel fibres. They proved to significantly enhance limited mechanical properties of concretes based on fine waste aggregates [7, 8] and thus promising achieving good results in case of WCA.

The size and shape of the aggregate particles significantly influences the fibre spacing [9, 10]. In comparison to natural aggregate which comprises of sphere-like grains, the WCA particles are of irregular shape and in many cases look like small blades. Such irregularities in WCA geometry are very likely to cause local fibre agglomeration (fibre balls) and non-homogeneous fibre distribution. The main objective of the planned research programme was to bypass all technological problems associated with WCA and steel fibre reinforcement used simultaneously. WCA composite achieved this way, would have versatile applications. Apart from secondary structural elements and common industrial floors, road pavements would be the most promising areas of implementation of this composite. The developed fresh mix should be characterized by good workability guarantying easy casting and compaction. The hardened composite should be characterized by mechanical properties enabling harnessing it as a structural material without limitations. Successful merging of cement matrix based on WCA and fibre reinforcement would create new opportunities for sustainable development of construction industry.

2 USED MATERIALS

Ceramic debris of construction origin was used as a raw material for WCA production. The ceramic waste consisted of broken and crushed wall blocks, hollow bricks and wire-cut bricks. The waste was partially contaminated by ordinary cement mortar. This kind of ceramic debris is very common all over Europe [6]. It represents the waste characteristic for building construction industry. The waste emerges during the very production of ceramic elements, transportation to the building site, the execution of construction (e.g. facades, partition walls) and execution of subsequent works (e.g. opening grooves etc.) [11]. The preparation of the used WCA consisted of two main stages. The first stage consisted of grounding the raw ceramic waste was for 5 minutes in an electric industrial grinder [4]. As a result of this process there was obtained waste all-in-aggregate. The second stage covered separating fine WCA fractions (characterized by the diameter φ < 1mm) and coarser WCA fractions (31.5 mm $\geq \varphi \geq$ 1 mm). The grading curve of used coarse WCA fractions prepared with the help of rectangular sieve set (according to EN 933-1:1997) was presented in [4, 12]. Loose bulk density and compacted bulk density of the WCA in question were equal to 948 kg/m^3 and 1170 kg/m^3 respectively. Water absorptivity by weight was equal to 22 %.

Tap water (EN 1008:2002) was used to prepare the mixes. A highly effective superplasticizer (type FM) containing silica fume and characterized by density equal to 1.45 g/cm^3 was used to ensure the consistency of all mixes. All mixes were modified by dosage of 1 % of the superplasticizer. The superplasticizer and its influence on properties of the fresh mix was described in previous work [8]. Portland cement CEM I 42.5 (EN 197-1:2000) was utilised as a binder. Sand of post-glacial origin washed from all-in-aggregate during hydroclassification process was used as fine aggregate. Only commercially available steel fibres were considered as fibre reinforcement. Hooked steel fibres made from cold drawn wire, as the most popular type used in civil and structural engineering, were selected. A geometrical characteristic of chosen fibre is presented in Fig.2. Mechanical properties and geometrical characteristics [13] of these fibres are summarized in Tab.1.

Fig. 1: Ground ceramic waste used as a coarse aggregate

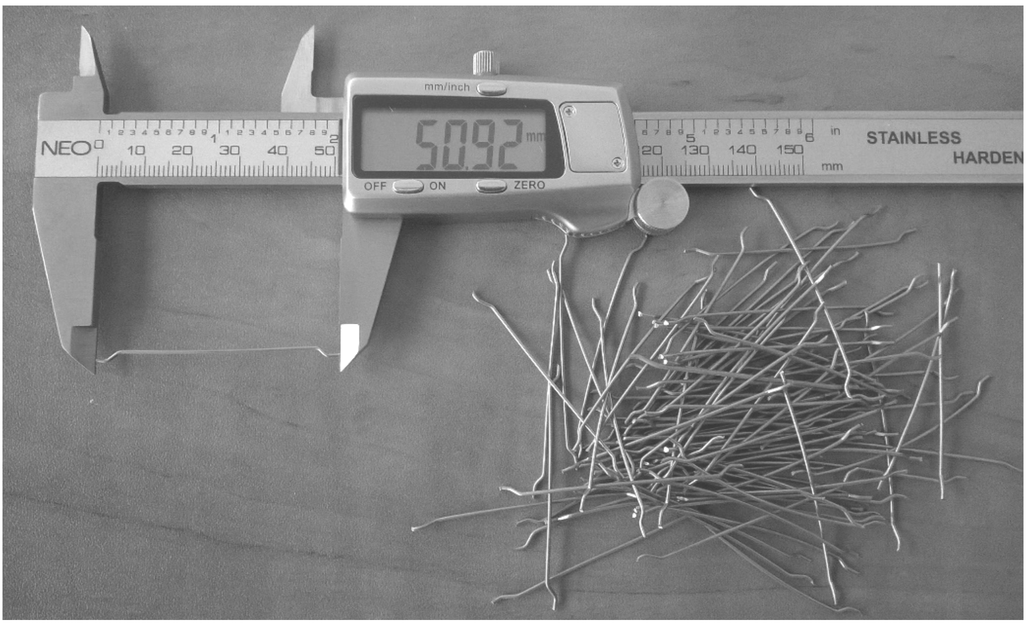


Fig. 2: A geometrical characteristic of used steel fibre

Tab. 1: Mechanical properties and geometrical characteristics of used fibres

L [mm]	d [mm]	L/d [-]	*FIER* [mm]	Hook geometry	R_m [MPa]	Ductility [-]	Steel [-]
EN 14889-1: 2006		-	$(\Psi \cdot L)/A$ [13]	$l + (a^2 + h^2)^{0.5}$	EN ISO 6892-1: 2009	EN 10218-1: 1994	EN 14889-1: 2006
50	1.00	50	12.279	6.228	935	9	Group I

3 MIX PROPORTIONING

It is impossible to apply traditional methods of concrete mix preparation for concrete based on WCA due to its large absorptivity. To guarantee stable and homogeneous properties of the fresh concrete mixes, WCA was pre-saturated for 7 days using tap water. This quite long pre-saturating period was needed to achieve full and uniform saturation of WCA. Pre-saturation is essential for enabling easy handling and mixing of fresh WCA concrete mix. It is also crucial to benefit from internal wet curing ("autogenous curing") [14–21]. The computed theoretical mix design was amended to accommodate water absorbed by WCA. The fully saturated 830 kg of WCA carry 182.6 kg of water. Some of this water directly influences the consistency and some influences only the curing process. Due to the WCA full saturation the amount of water was reduced to 92 kg/m^3. For all cast mixes, fully saturated WCA and 92 kg/m^3 of water were enough to maintain stable consistency. All fresh mixes were characterized by consistency class C2 tested according to EN 12350-4:2009. The mix design of unreinforced matrix is presented in Tab. 2.

Tab. 2: Mix proportions per 1 m^3

Ingredient	WCA	Sand	Cement	Water	Superplasticizer
[kg]	830	652	307	92	3.1

A rotary drum mixer was utilized to prepare WCA mixtures. Compaction of fresh concrete mixes was performed externally using a vibrating table. Each specimen was vibrated in two layers for 20 s with each layer filling half of the thickness. The vibration period was long enough to observe a thin film of bleed water appearing on the surface. Initially, the specimens were kept in their moulds covered with polyethylene sheets for 24 h. For the next 27 days, after removing from their moulds, the specimens were cured by storing them in a water tank (Temp: +21^{o}C).

4 RESEARCH PROGRAMME

The WCA matrix was reinforced by steel fibre in following volumes: 0.5 %, 1.0 % and 1.5 %. Cast specimens were in a form of cubes (150 mm · 150 mm · 150 mm), cylinders (φ=150 mm, h=300 mm), beams (b=150 mm, h=150 mm, l=700 mm) and circular plates (φ=1000 mm, h=100 mm). Cubes and cylinders were used for compressive strength tests and splitting tensile strength tests according to EN 12390-6:2009. Prismatic specimens were used to test flexural tensile strength according to EN 14651:2005 and shear strength (according to JCI-SF6). The flexural tensile strength was tested according to the limit of proportionality (LOP) method (EN 14651:2005). During the flexural test the deflection and the crack mouth opening displacement (CMOD) were measured for all beams. For evaluating the residual tensile strength (f_R), the responses of the fibre reinforced cement composite (FRCC) beams at CMOD 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm were of special interest. Circular plates were used for impact tests. In order to carry on the impact tests the adequate laboratory stand was built from steel modular elements characterized by high load bearing capacity. Tested plates were mounted on three massive supports located on the circumference. A schematic localization of a plate, plate supports and impact area is presented in Fig. 3. During the test, a plate was loaded by the free fall of 40 kg mass from the height of 1.0 m.

a)

b)

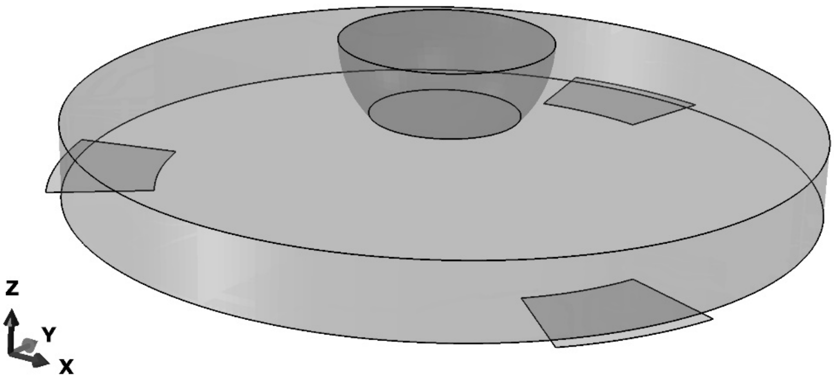


Fig. 3: Lab stand for impact tests (a)
and a schematic localization of the supports and impact area (b)

5 ACHIEVED RESULTS

Results of density of hardened WCA fibre reinforced concretes are presented in Fig. 4. The matrix is characterized by density of 2001 kg/m^3. The density increases along the increase of the addition of fibre, to achieve the value of 2075 kg/m^3 for WCA composite reinforced by 1.5 % of fibre.

Results of compressive strength are presented in Fig. 4. The tests were conducted on cubes and cylinders (according to EN 206-1) to enable full comparison with strength classes of ordinary concrete. The addition of fibre obviously increases the compressive strength. The differences between cylinder and cube strength are getting larger and larger with the increase of fibre volume. Unreinforced WCA composite is characterized by compressive strength of 27.9 MPa and 39.1 MPa for cylinder and cube specimens respectively. The cylinder and cube compressive strengths for composite reinforced by 1.5 % of fibre are equal to 36.1 MPa and 51.8 MPa. The difference between both strengths exceedes 15 MPa. According to EN 206-1 (ordinary concrete) this difference should be close to 10 MPa. It proves that the strength class dedicated for ordinary concrete is subjected to large inaccuracy and provides misleading information in case of fibre reinforced WCA composites. Results of tensile and shear strength of WCA fibre reinforced concrete are presented in Fig. 6.

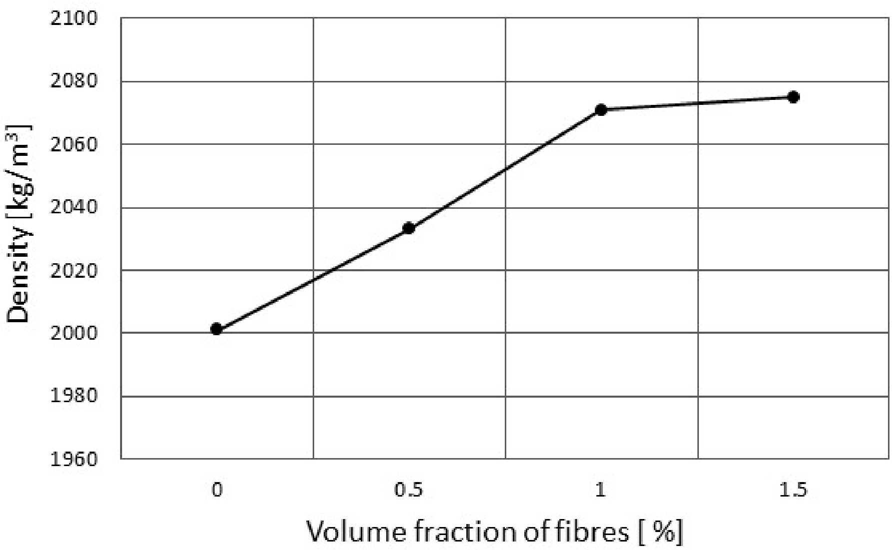


Fig. 4: Density of WCA fibre reinforced concrete

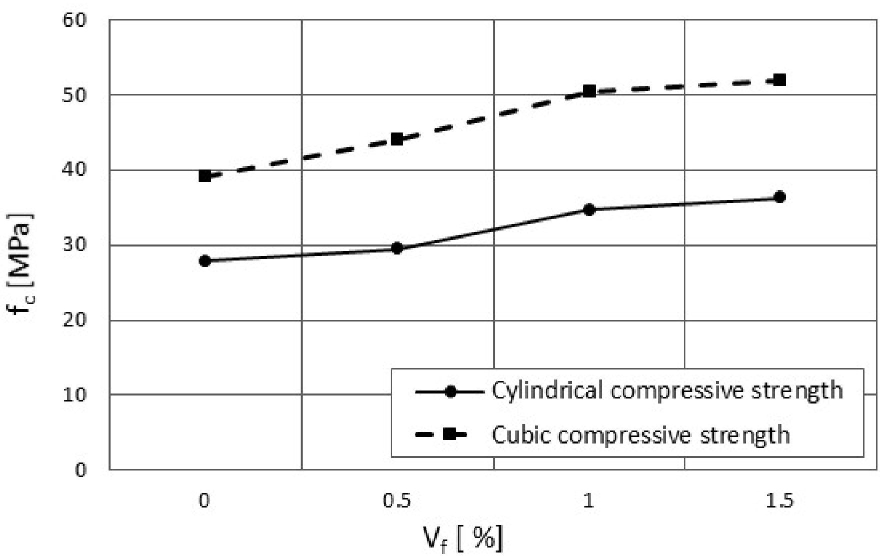


Fig. 5: Compressive strength of WCA fibre reinforced concrete

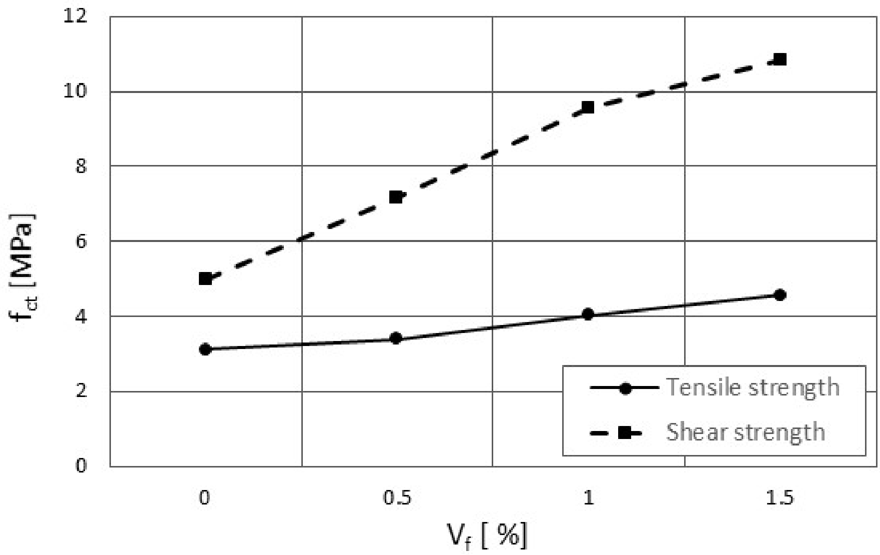


Fig. 6: Tensile and shear strength of WCA fibre reinforced concrete

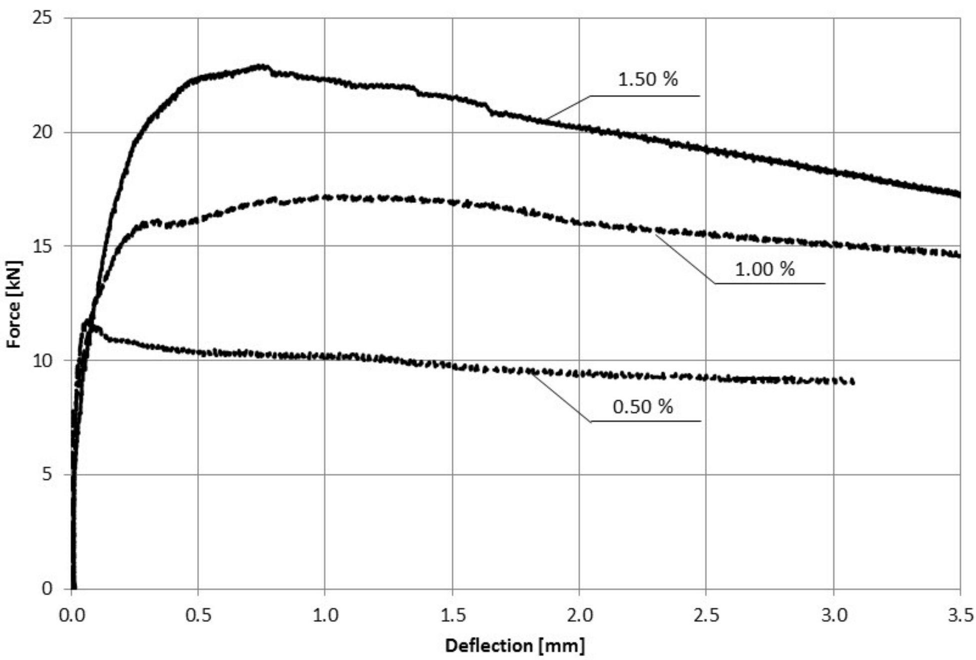


Fig. 7: Flexural characteristics of tested WCA composites

Results of the tests of flexural tensile characteristics of WCA fibre reinforced composites are presented in Fig. 7. Achieved force–deflection relations allowed to determine residual flexural strengths: f_{LOP}, $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$. It is commonly assumed that residual strengths $f_{R,1}$ and $f_{R,3}$ characterize service (SLS) and ultimate (ULS) conditions respectively. Values of all five residual strengths (determined according to EN 14651:2005) are presented in Tab. 3. There were also calculated and presented values of two factors [dimensionless]: $f_{R,3} / f_{R,1} > 0.5$, $f_{R,1} / f_{LOP} > 0.4$. These factors are crucial for assessing if conventional reinforcement substitution is enabled. This knowledge allowed to assess the strength class of tested WCA composites.

Tab. 3: Residual strengths and strength class of tested WCA composites

Residual flexural tensile strength [MPa]	Volume fraction of fibres		
	0.5 [%]	1.0 [%]	1.5 [%]
f_{LOP}	3.1	2.6	2.7
$f_{R,1} > 1.5$	3.7	5.1	6.5
$f_{R,2}$	3.4	5.4	7.2
$f_{R,3}$	3.3	5.4	6.9
$f_{R,4} > 1.0$	3.3	5.1	6.5
$f_{R,3} / f_{R,1} > 0.5$	0.89	1.06	1.06
$f_{R,1} / f_{LOP} > 0.4$	1.2	2.0	2.4
Strength Class	3b	5c	6c
–	Conventional reinforcement substitution is enabled		

One can noticed that value of f_{LOP} is very similar for all three WCA fibre reinforced composites (2.8 MPa ± 0.2 MPa). It means that tension–CMOD relation is similarly steep, at least for CMOD values from 0.000 mm to 0.005 mm. It has its resemblance in the values of modulus of elasticity. The changes in values of modulus of elasticity are small. Its values range from 22 GPa to 25 GPa. Achieved values of residual strengths $f_{R,1}$ and $f_{R,4}$ of all tested WCA fibre reinforced composites are larger than minimum conditions defined by EN-14889-1:2006 (1.5 MPa and 1.0 MPa respectively).

6 NUMERICAL SIMULATION

Adequate numerical models for tested slabs have been prepared in order to perform numerical analysis using Finite Element Method. Explicit procedure of integration for equations of motion [22] was used (ABAQUS/Explicit computer code [23]) due to impulsive character of applied load (direct impact). Main geometric features and assumptions concerning analysis were the same. The only differences regard the description of material characteristics for analysed group of plates. Concrete slabs and impactor were modelled as three-dimensional deformable solid bodies discretized using three-dimensional 8-node linear solid elements. The supports were discretized with three-dimensional quadrilateral rigid elements. The master–slave type of contact [23] between the impactor and the plate, as well as between the plate and the supports has been introduced. A schematic view of the assumed numerical model is presented in the Fig. 6.

The dynamic response of plates is conditioned by material characteristics of applied materials and the quantity and distribution of fibres in the volume. The adequate script to create the numerical model was prepared by authors using Python programming language (included in ABAQUS computer code environment) [23]. The script creates the entire discrete model of the problem (input file for FEM computer code ABAQUS/Explicit), with all geometric, material and other necessary data. The distribution of fibres was randomly calculated by pseudo-random number generation where the random position of each fibre is defined by coordinates of its centre of gravity and adequate angles of inclination. Additionally, the information about spatial distribution of fibres in structural elements have been taken into account (for example: contribution of fibres with various inclination angles, distribution in thickness, etc. [24]).

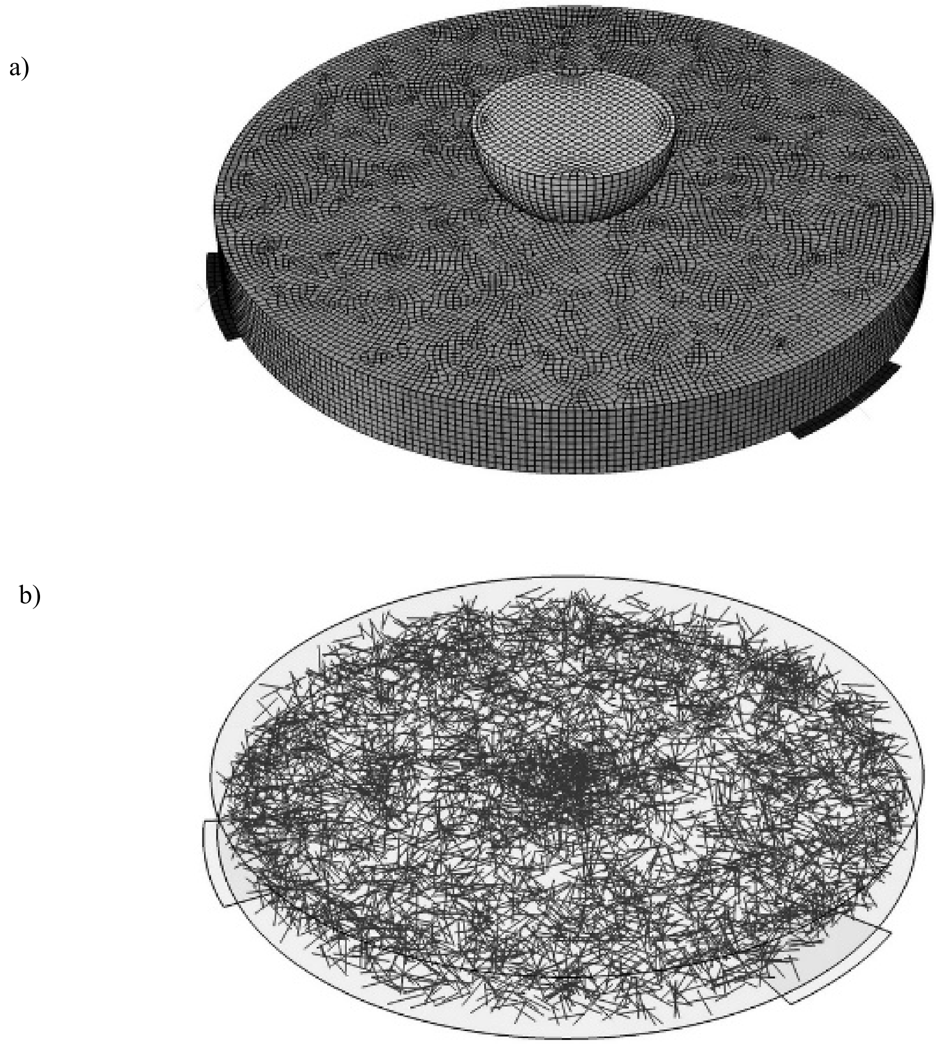


Fig. 8: Finite element mesh (a) and randomly distributed fibres (b)

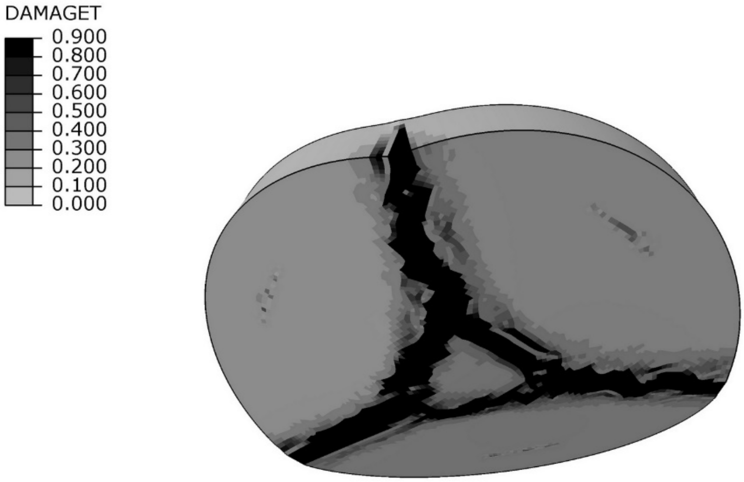
Based on independent randomness several numerical models for each analyzed slab were defined, and the adequate slightly different patterns of damage were obtained as the result of analyses.

Steel fibres were modelled using three-dimensional truss finite elements, and elasto-plastic material model with isotropic hardening. For concrete matrix the *Concrete Damage Plasticity* [23] material model was assumed, taking into account the damage characterized by two independent scalar parameters. In this model the elasto-brittle material behaviour has been assumed for tension, and a classic elasto-plastic response for compression. More detailed information is available in [25, 26]. The similar material model was successfully verified and applied in former analyses [27–32]. An adequate interaction between concrete matrix and steel fibres has been enabled by insertion of randomly distributed “cloud” of finite elements of fibres into concrete volume of solid finite elements. The application of embedded elements definition [23] allowed for interaction of two different meshes of finite elements, one inserted into other. The whole mesh of finite elements and an example of random distribution of fibres is presented in Fig. 8.

Selected results concerning the distribution of damages in a plate with and without reinforcement (steel fibres 50 × 1.0 mm, reinforcement 0.5 %) are given in Fig. 9. The whole set of results is available in [33], with adequate analysis and discussion of results.

Numbers of impacts necessary to damage the plates obtained in numerical analyses, correspond to the values achieved during the experimental tests. The only problem is to find out the criterion which allows to decide whether the plate is damaged or not. In experimental tests this was quite obvious and visible – the plate lost its integrity and separated into a few parts. In numerical analyses, this total separation was difficult to evaluate and needed the observation of whole energies of the system (i.e. increase of kinetic energy for a longer period of time).

a)



b)

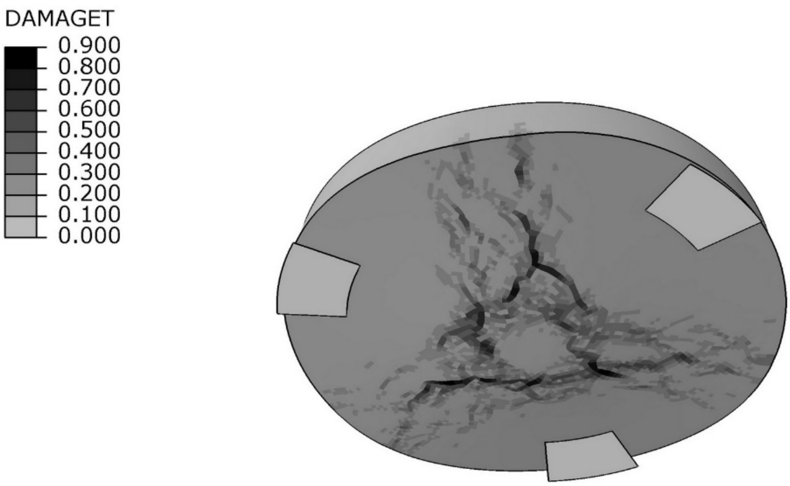


Fig. 9: Distribution of damages: a) for plate without reinforcement after first impact – bottom view, b) for reinforced plate after first impact – bottom view

The basic static material characteristics for the fibre reinforced concrete does not vary very much with percentage of reinforcement and the type of applied fibres contrary to the dynamic response where the overall behaviour is conditioned strongly by these factors. The number of impacts necessary to damage the plate show great differences obtained for various types of plates. If the plate without any reinforcement is damaged totally after the first impact of 40 kg weight dropped from 1 m height, a similar plate with 1.5 % of fibres (60 × 0.75 mm) is able to withstand 70 of such impacts. Also the damage patterns obtained for non-reinforced plates and for plates with reinforcement are different: a large number of fibres in the entire volume of concrete gives a large number of small cracks distributed through the entire plate. Although in all cases the formation and development of primary cracks (mainly three) is observed, for plates with 1.5 % of reinforcement the cracks do not divide the plate into independent parts, due to their dispersed pattern. In this last case it is difficult to individuate separated parts of the slab, they are linked together by numerous undamaged fibres – the formed cracks have still a residual resistance [33].

The main scope of numerical simulation of performed experimental tests was to check the adequacy of assumptions concerning a finite element model of the entire phenomenon, especially the applied material models for concrete and fibres, the assumed model of contact between various parts of the model (impactor – plate – supports) and other parameters governing the nonlinear dynamic analysis. Former attempts, where the composite fibres-concrete was homogenized in order to obtain an equivalent fictitious material which presents the same behaviour as the analysed composite, were rather unsuccessful. Due to this fact, the random distribution of fibres was assumed, and an adequate script in Python programming language, included in ABAQUS computer code environment had been written and used to embed the fibres (i.e. truss elements) into concrete matrix (three dimensional solid elements). The obtained results are very promising, allowing to consider nonhomogeneous structure of the material in numerical simulations of such complex phenomena.

7 CONCLUSION

On the basis of conducted research programme the following conclusions were drawn:

- Using strength class of ordinary concrete to describe fibre reinforced WCA composites is subjected to large inaccuracy and may provide misleading information.
- Tested fibre reinforced WCA concretes are characterized by mechanical properties enabling substitution of conventional reinforcement.
- Experiments allowed to describe the development of damage patterns in a function of a number of impacts for various reinforcement percentages and fibre types. Additionally the secondary effects (local zones damaged in compression, areas of distributed cracks, etc.) revealed during the entire phenomena were registered and documented.
- Tests performed on the entire set of plates show that the presence of fibres in concrete matrix significantly influences a dynamic response to impact loads. In this way it is possible to obtain the impact-resistant material, produced from waste aggregate.
- Application of WCA gave additional features concerning the regularity of cracks, which can propagate through the ceramic aggregate (brittle in tension), without complex damage patterns observed for traditional mineral aggregate.
- The analysis of numerical results show their consistency with experimental tests, in terms of damage patterns, their development with subsequent impacts, and the number of impacts necessary to damage totally the plate.
- The same discrepancies between experimental and numerical results were observed, especially concerning localization of primary cracks, development of secondary cracks in time and maximum displacement obtained for the plate's central point (due to relatively simple material model applied for concrete – justified by computational needs, and assumed simple interaction between fibres and concrete matrix, etc.). Such differences do not influence general consistency

between experimental tests and numerical analyses, proved by numerous comparative analyses performed on experimental and numerical results [33].

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