ŚRODKOWO-POMORSKIE TOWARZYSTWO NAUKOWE OCHRONY ŚRODOWISKA
Rocznik Ochrona Środowiska
Tom 14. Rok 2012 ISSN 1506-218X 69–80

Load-CMOD Characteristics of Fibre Reinforced Cementitious Composites Based on Waste Ceramic Aggregate

Jacek Domski, Jacek Katzer, Dariusz Fajto
Koszalin University of Technology, Poland

1. Introduction

Ceramic waste from construction industry is probably the most important part in the global volume of construction and demolition waste [5]. Worldwide, there is a growing research effort to successfully harness ceramic waste in construction industry [7, 16]. In case of technology of concrete, one of the most promising applications of ceramic waste is using it as a coarse aggregate for concrete. Concrete and other cementitious composites are the most commonly applied construction materials in the world. The main component of any cementitious composite is aggregate which covers from 60% to 80% of a composite volume. Global annual production of concrete, mortar and other cementitious composites consumes 20 billion tonne of different aggregate. It means that about 3 tonne of aggregate is used per person per year, which considerably influences natural environment. The production of ordinary concrete usually consumes coarse aggregate (e.g. gravel) and fine aggregate (e.g. sand) in weight proportion approximately equal to 3:1 [17]. There are vast areas of the world characterized by considerable excess of fine aggregate and deficiency of coarse aggregate [10]. Such natural conditions cause inefficient and unbalanced use of existing resources of mineral aggregate. Coarse aggregate in some cases is obtained from all-in-aggregate by a hydroclassification process which consumes large quantities of water and energy, leaving waste heaps of rinsed sand. On the other hand producers of concrete are often forced to organize a long distance transport of aggregate of specific grading, which is obviously associated with a significant contribution to carbon dioxide emission. Waste ceramic aggregate can be an answer to this problem solving two urgent ecological issues at the same time: utilising large volumes of construction/demolition waste and providing locally available coarse aggregate in areas where it is in constant demand.

So far waste ceramic aggregate was usually used to cast elements characterized by less demanding mechanical characteristics, such as pavement slabs [3]. One of the main issues associated with replacing traditional coarse aggregates by waste ceramic aggregate (WCA) is the homogeneity of mechanical properties of cast concrete and mechanical properties themselves. To bypass those technological problems authors decided to embrace a new approach to the problem and modify concrete mix based on WCA by an addition of engineered steel and polymer fibre. So far steel fibre proved to be a very good solution for limited mechanical properties of concrete based on other waste aggregates [9] and thus promising achieving satisfactory results in case of WCA.

2. Waste Ceramic Aggregate

Ceramic waste used as a raw material for production of waste ceramic aggregate was of construction origin. This ceramic debris consisted of crushed bricks, hollow bricks and ceramic wall blocks contaminated by cement mortar. Such ceramic waste is typical for ordinary construction process and it appears during transportation to the building site, during the execution of several construction elements (e.g. facades, partition walls) and on subsequent works, such as the opening grooves [5]. The process of preparation of WCA consisted of two main stages. During the first stage the ceramic waste was ground for 5 minutes in an electric industrial grinder. There were used 21 steel spheres characterized by mass varied from 1343 g to 2650 g. As a result of grinding there was obtained a mixture of fine and coarse fractions of waste ceramic aggregate. Ceramic waste and ground ceramic waste are presented in Fig. 1.

The second stage of preparation of WCA consisted of separating fine and coarse fractions of ground ceramic waste. A mechanical sieve set was employed to separate fine (< 1 mm) and coarse fractions (≥ 1 mm). The sieve analysis of coarse fractions was performed using a rectangular sieve set (according to EN 933-1:1997). Achieved grading characteristics is presented in Fig. 2.

Fig. 1. Ceramic waste and ground ceramic waste
Rys. 1. Gruz ceramiczny i zmielony gruz ceramiczny

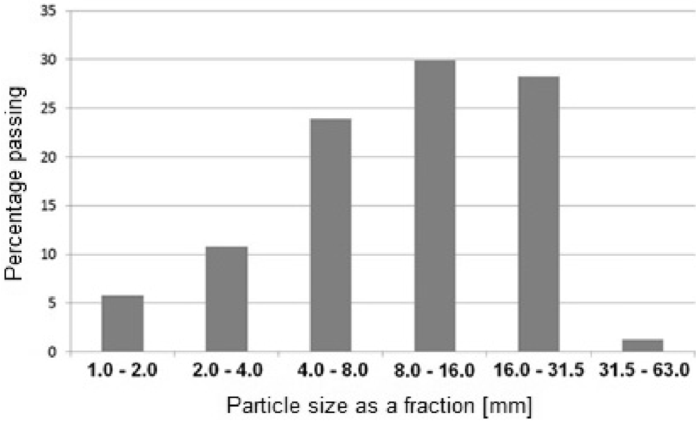

Fig. 2. Grading of coarse WCA
Rys. 2. Uziarnienie grubego ceramicznego kruszywa odpadowego

Loose bulk density and compacted bulk density was equal to 948 kg/m^3 and 1170 kg/m^3 respectively. Water absorptivity by weight was equal to 22%. Significant absorptivity of the WCA made it impossible to apply traditional methods of concrete mix preparation. To guarantee stable properties of the fresh concrete mix, WCA was pre-saturated for 7 days in tap water. Such a long term of pre-saturating was needed to achieve full and uniform saturation of WCA. Pre-saturation, apart for enabling easy handling and mixing of fresh WCA concrete mix, allowed to benefit from internal wet curing ("autogenous curing"). The concept of internal wet curing is based on the use of internal reservoirs providing a source of water to the cement paste to offset self-desiccation phenomenon. Pre-saturated WCA gradually releases water to replace the water used during hydration reactions. The idea that self-desiccation can be counteracted by a partial replacement of ordinary aggregate by pre-saturated porous aggregate was successfully demonstrated by various authors [15, 20, 21] and it has been proved that harnessing porous aggregate for internal curing mitigates or completely eliminates autogenous shrinkage of concrete [1, 4, 13, 22, 23]. The efficiency of an internal curing phenomenon is strongly related to both the content and the parameters of the used porous aggregate (e.g.: water absorption, pore structure, grain size distribution, volume of open and closed voids etc.). Basically the paste-aggregate proximity is a decisive factor determining the radius which the internal curing water should readily penetrate.

3. Cement, Fibre and Other Materials

Portland cement CEM I 42.5 (EN 197-1:2000) and tap water (EN 1008:2002) were used in all mixtures. Waste sand of post-glacial origin was employed as a fine aggregate. This sand and its applications in different cementitious composites were described in numerous previous publications [9, 11, 12]. All cast mixes were modified by admixture of 1% of highly effective superplasticizer (type FM) containing silica fume and characterized by density equal to 1.45 g/cm^3. The influence of this admixture on properties of the fresh mix was described in previous work [9]. There were used two types of engineered fibre: hooked steel fibre and continuously embossed polymer fibre. Those fibres represent the most popular types of fibres widely used in civil and structural engineering industry [8]. Mechanical and geometrical characteristics of both types of fibres are summarized in Tab. 1.

Table 1. Properties of used fibre
Tabela 1. Właściwości zastosowanych włókien

	Steel Fibre	Polymer Fibre
Length [mm]	30	48
Diameter [mm]	0.55	n/a
Aspect Ratio [–]	55	~50
Specific gravity [kg/m^3]	7860	910
Tensile Strength [MPa]	>1100	550
Modulus of Elasticity E [GPa]	210	6
Number of fibres per 1 kg	16750	35000

4. Mix Design, Curing and Casting

The concrete mix was designed according to a “double enfolding method”. This method is focused on creating sufficient amount of cement paste enfolding grains of fine aggregate and sufficient amount of mortar enfolding coarse aggregate. In this way very tight mix is achieved and other properties (e.g. compressive strength) are the result of this tightness. The mix design of 1 cubic meter was as follow: WCA – 830 kg, sand – 652 kg, cement – 307 kg, water – 216 kg, superplasticizer – 3.1 kg. This mix design was then scaled to accommodate water absorbed by WCA. 830 kg of WCA after being fully saturated carry 182.6 kg of water. Some of this water directly influence the consistency and some influence only the curing process. The amount of water was reduced to 92 kg/m^3. Fully saturated WCA and 92 kg/m^3 allowed maintaining stable consistency for all cast mixes. There were prepared concrete mixes reinforced by 0.5% and 1.0% of steel or polymer fibre (by volume).

Specimens were in a form of cubes (150 mm·150 mm·150 mm), cylinders (□ = 150 mm, h = 300 mm) and beams (150 mm·150 mm ·700 mm). There were cast six cubes, six cylinders and three beams per one FRCC batch. A rotary drum mixer was used to prepare composite mixtures. Compaction of fresh concrete mix was performed externally using a vibrating table. Each specimen was vibrated in two layers, with each layer filling half of the thickness. Each layer was vibrated for 20 s (until a thin film of bleed water appeared on the surface). The first step of curing was to keep the specimens in their moulds covered with polyethylene sheets for 24 h. Subsequently the specimens were demoulded and cured by storing them in a water tank (Temp: +21°C).

5. Research Programme

The programme of experiments was divided into three main stages. The objective of the first stage was to determine the density and compressive strength of the composites in question. The second stage was to conduct the ultrasonic pulse velocity tests. An apparatus with two transducers (one pulse generator and one receiver) was employed to generate an ultrasound pulse with a frequency of 54 kHz. The test was carried out at one observation point at a time. The transducers were located opposite each other creating a direct transmission of the wave. This kind of transmission was employed as the most sensitive. The third phase of the research involved measuring the flexural tensile strength according to the limit of proportionality (LOP) method (EN 14651:2005). The third stage covered flexural tests of beams. The three-point flexural test was chosen as the most reliable one in comparison to four-point tests. In case of three-point test, beam is formed with a notch and the first crack always appears in the vicinity of the mid-span. In case of four-point test the test beam is formed without a notch and the first crack appears at the weakest cross section and the location of the crack cannot be predicted. The crack mouth opening displacement (CMOD) was measured for all tested beams. In the case of 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. The loading rate was equal to 0.2 mm/min and load-CMOD curves were measured. The examination results were statistically processed, and values bearing the gross error were assessed on the basis of Grabbs criterion [2]. The objectivity of the experiments was assured by the choice of the sequence of the realization of specific experiments from a table of random numbers.

6. Results

Workability of all the mixes tested according to the Vebe procedure was ranging from t_{Vebe}=11 s to t_{Vebe}=12 s (workability class V2 according to EN 206-1). The results of ultimate compressive strength and density of analysed FRCC constituting the first stage of the research programme are summarized in Tab. 2.

Table 2. Density and compressive strength
Tabela 2. Gęstość i wytrzymałość na ściskanie

	Matrix	Fibre [%]			
		Steel 0.5	Steel 1.0	Polymer 0.5	Polymer 1.0
ρ [kg/m^3]	1926.0	2001.8	1982.5	1934.2	1880.5
f_{cube} [MPa]	47.1	48.7	51.0	46.7	38.2

During the second stage of the research programme the ultrasonic pulse velocity for all composites was determined. The velocity for composite modified by Steel Fibre 0.5%, Steel Fibre 1.0%, Polymer Fibre 0.5%, Polymer 1.0% and matrix was equal to 3717 m/s, 3627 m/s, 3669 m/s, 3518 m/s and 3649 m/s respectively. Once the velocity is determined, an idea about quality, uniformity, condition, and strength of the tested cement composite can be attained. Velocity of ultrasonic pulse classifies the quality of tested concrete [19]. Velocity range V > 4.5 km/s, 4.5km/s > V > 3.5 km/s and 3.5 km/s > V > 3.0 km/s defines quality of concrete as excellent, good and medium respectively. Using this classification examined cement composite mixes are characterized by good quality. The wave velocity, in a homogeneous, isotropic and elastic medium is related to the dynamic modulus of elasticity, by the expression [17]:

$$E_d = \rho \cdot V^2 \tag{1}$$

Where:

ρ – density [kg/m^3],
V – wave velocity [m/s].

This relation can be used for the determination of the dynamic modulus of elasticity and hence as a means of checking the quality of concrete. Therefore, the test is useful to detect voids, deterioration due to frost or fire, and uniformity of concrete in similar cast elements [10, 14, 17]. Cement composite does not fulfil the physical requirements for the validity of the above expression, but some researchers [6, 19] have found it very useful to control and observe high strength concrete structures in service. Dynamic moduli of elasticity calculated for FRCC in question are presented in Fig. 3. Results of the third stage of the research programme in a form of Load-CMOD diagrams are presented in Fig. 4.

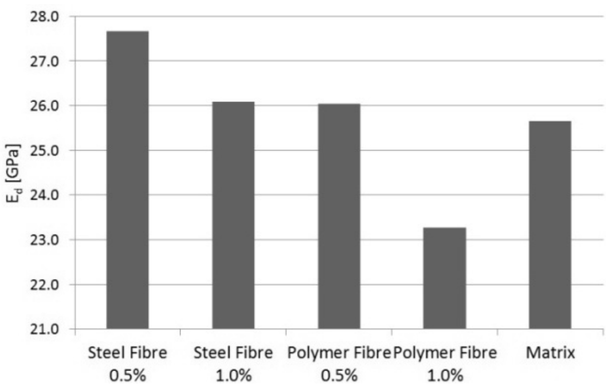

Fig. 3. Dynamic modulus of elasticity
Rys. 3. Dynamiczny moduł sprężystości

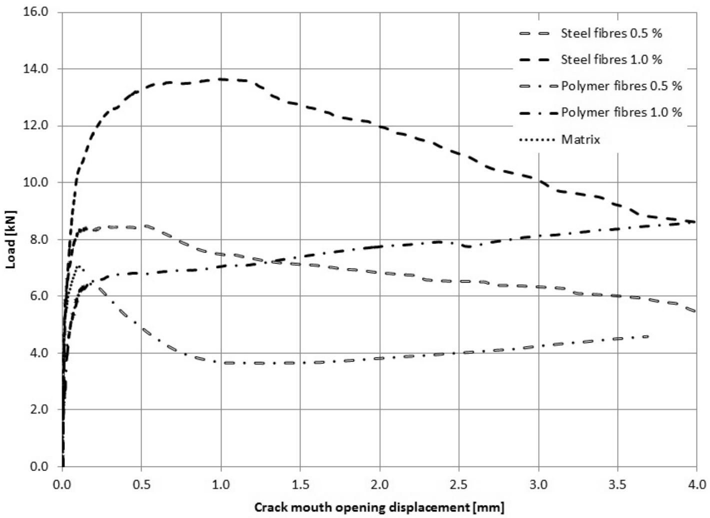

Fig. 4. Load – CMOD diagrams
Rys. 4. Zależności obciążenie – CMOD

On the basis of Load – CMOD diagram, European Standard EN 14651:2005 "Test method for metallic fibered concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual)" requires four different values of the residual strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}) to be calculated. Values of the residual strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}) for FRCC in question are presented in Fig. 5. These strengths corresponding to different values of the CMOD are difficult to incorporate to FRCC design procedures [18]. Therefore it was assumed that residual strengths f_{R1} and f_{R3} which are significant for service and ultimate conditions respectively, will characterize the global residual strength. This strength would be harnessed for serviceability limit states (SLS) analysis and ultimate limit states (USL) analysis. To further simplify the classification it was proposed in "fib Bulletin 55, Model Code 2010" that material behaviour at ULS will be related to the behaviour at SLS employing the f_{R3}/f_{R1} ratio. Basically, in order to classify the post-cracking strength of FRCC a linear elastic behaviour can be assumed by considering the characteristic residual strength significant for service (f_{R1}) and ultimate (f_{R3}) conditions. According to this procedure FRCC post-cracking residual strength is described by two parameters: namely f_{R1} (representing the strength interval) and a letter a, b, c or d (representing the ratio f_{R3}/f_{R1}).

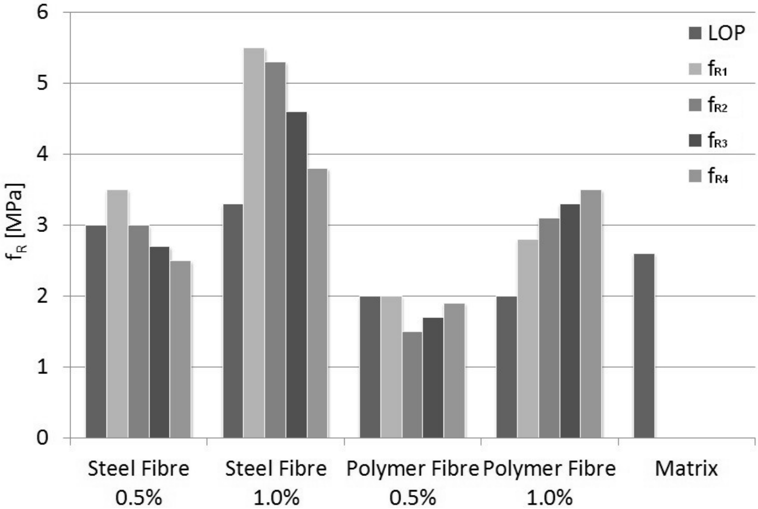

Fig. 5. Residual flexural tensile strength
Rys. 5. Rezydualna wytrzymałość na rozciąganie przy zginaniu

This classification properly represents the most common cases of FRCC softening and hardening. Traditional reinforcement substitution is enabled if both of the following relationships are fulfilled:

$$f_{R1}/f_{LOP} > 0.4 \tag{2}$$
$$f_{R3}/f_{R1} > 0.5 \tag{3}$$

Full classification of tested FRCC according to "fib Bulletin 55, Model Code 2010" is summarized in Tab. 3.

Table 3. FRCC classification in compliance to "fib Model Code"
Tabela 3. Klasyfikacja FRCC zgodnie z "fib Model Code 2010"

	Fibre [%]			
	Steel 0.5	Steel 1.0	Polymer 0.5	Polymer 1.0
f_{R1} [MPa]	3.5	5.5	2.0	2.8
f_{R3}/f_{R1}	0.771	0.836	0.850	1.178
Class	3.0b	5.0b	2.0b	2.5d
f_{R1}/f_{LOP}	1.167	1.667	1.000	1.400
Reinforcement substitution	enabled	enabled	enabled	enabled

7. Discussion and Conclusions

This paper summarizes the results of an experimental programme carried out to study the possibilities of creating FRCC based on WCA and using it as a structural material. The main problem of harnessing ceramic coarse aggregates as a substitute of natural aggregates is its higher water absorption. The texture and greater absorption characteristics of WCA result in an increase in water demand in order to maintain desired workability. This technological problem can be avoided by pre-saturating WCA. At the same time one benefits from internal wet curing phenomenon. The main benefit of internal water curing provided by the pre-saturated WCA is an improvement of cement hydration reaction which results in achieving significant compressive strength of the composite in comparison to compressive strength of waste ceramic used as an aggregate. Aggregate interlock and bond between cement matrix and the fibre reinforcement are mechanisms that seem to work correctly in all analysed cases. Steel fibre reinforcement, in comparison to polymer fibre reinforcement, was more effective in achieving higher both compressive and flexural tensile strengths (although matrix modified by polymer fibres was characterized by higher relation f_{R3}/f_{R1}). The results of this experimental study indicate that the harnessing WCA for the production of non-structural and secondary structural FRCC elements would be possible and promising to be feasible. This research work forms the basis for further experiments on FRCC with the use of WCA. Testing large scale specimens would be the most desired area of scientific interest.

Acknowledgments

The conducted research programme was realized as a part of research project entitled “Impact resistant concrete elements with nonconventional reinforcement” and founded by Polish “National Science Centre” (decision number: DEC-2011/01/B/ST8/06579).

References

1. **Bentur A., Igarashi S., Kovler K.:** *Prevention of autogenous shrinkage in high strength concrete by internal curing using wet lightweight aggregates.* Cement and Concrete Research 31 (11), 1587–1591 (2001).
2. **Borovikov I.P., Borovikov V.P.:** *STATISTICA: Data Preparation and Analysis*. Moscow, Filini. 1998.
3. **de Brito J., Pereira A.S., Correia J.R.:** *Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates.* Cement and Concrete Composites, 27(4), 429–433 (2005).
4. **Collins F., Sanjayan J.G.:** *Strength and shrinkage properties of alkali-activated slag concrete containing porous coarse aggregate.* Cement and Concrete Research 29(4), 607–610 (1999).
5. **Correia J.R., de Brito J., Pereira A.S.:** *Effects on concrete durability of using recycled ceramic aggregates.* Materials and Structures, vol. 39, 169–177 (2006).
6. **Hassen M., et al.:** *Ultrasonic measurements and static load tests in bridge evaluation.* NDT&E International, Vol. 28, No. 6, 331–337 (1995).
7. **Hendriks C.F., Janssen G.M.T.:** *Use of recycled materials in construction.* Materials and Structures, Vol. 36, 604–608 (2003).
8. **Katzer J.:** *Steel fibers and steel fiber reinforced concrete in civil engineering.* Pacific Journal of Science and Technology, vol. 7, no 1, 53–58 (2006).
9. **Katzer J.:** *Properties of Precast SFRCC Beams Under Harmonic Load.* Science and Engineering of Composite Materials, Vol. 15, No 2, 107–120 (2008).
10. **Katzer J., Kobaka J.:** *The assessment of fine aggregate pit deposits for concrete production.* Kuwait Journal of Science and Engineering, Vol. 33, Issue 2/2006, 165–174 (2006).
11. **Katzer J., Kobaka J.:** *Ultrasonic pulse velocity test of SFRC.* Proceedings, The 2nd Central European Congress on Concrete Engineering "Concrete Structures for Traffic Network", 21–22 September 2006, Hradec Kralove, Czech Republic, 389–392 (2006).
12. **Katzer J., Kobaka, J.**: *Harnessing Waste Fine Aggregate for Sustainable Production of Concrete Precast Elements.* Rocznik Ochrona Środowiska, Vol. 12, 33–45 (2010).
13. **Kohno K., et al.:** *Effects of artificial lightweight aggregate on autogenous shrinkage of concrete.* Cement and Concrete Research 29(2), 611–614 (1999).
14. **Komlos K., et al.:** *Ultrasonic Pulse velocity Test of Concrete Properties as Specified in Various Standards.* Cement and Concrete Composites, 18, 357–364 (1996).
15. **Kovler K., Jensen O.M.:** *Novel techniques for concrete curing.* Concrete International 27(9), 39–42 (2005).

16. **Müller A.:** *Lightweight aggregate produced from fine fraction of construction and demolition waste*. Design for Deconstruction and Materials Reuse. Proceedings of the CIB Task Group 39– Deconstruction Meeting, Karlsruhe, Germany. 2002.
17. **Neville A.M.:** *Properties of Concrete*. Longman, 4th Edition, Addison Wesley Longman, Harlow, Essex, England. 1995.
18. **Prisco M., Plizzari G., Vandewalle L.:** *Fibre reinforced concrete: new design perspectives.* Materials and Structures, vol. 42, 1261–1281 (2009).
19. **Qasrawi H.Y.:** *Concrete strength by combined non-destructive methods Simply and reliably predicted.* Cement and Concrete Research, 30, 739–746 (2000).
20. **Suzuki M., Meddah M.S., Sato R.:** *Use of porous ceramic waste aggregates for internal curing of high-performance concrete.* Cement and Concrete Research 39, 373–381 (2009).
21. **Weber S., Reinhardt H.W.:** *A new generation of high performance concrete: concrete with autogenous curing*. Advanced Cement Based Material 6(2), 59–68 (1997).
22. **Zhutovsky S., Kovler K., Bentur A.:** *Influence of wet lightweight aggregate on mechanical properties of concrete at early ages*. Materials Structure 35, 97–101 (2002).
23. **Zhutovsky S., Kovler K., Bentur A.:** *Influence of cement paste matrix properties on the autogenous curing of high-performance concrete.* Cement & Concrete Composites 26(5), 499–507 (2004).

Charakterystyka obciążenie – CMOD fibrokompozytów cementowych na bazie ceramicznego kruszywa odpadowego

Streszczenie

W artykule opisano badania kompozytów cementowych na bazie ceramicznego kruszywa odpadowego i modyfikowanych włóknami. W badaniach zastosowano dwa rodzaje włókien (stalowe i polimerowe) a ilość dozowanych włókien wahała się od 0% do 1,0% objętościowo. Przebadano podstawowe cechy mechaniczne omawianych fibrokompozytów takie jak: gęstość, czy wytrzymałość na ściskanie, ale główny nacisk badawczy został położony na wyznaczenie rezydualnych wytrzymałości na rozciąganie przy zginaniu zgodnie z EN 14651:2005. Wszystkim badanym fibrokompozytom przyporządkowano klasę wytrzymałościową zgodnie z nowymi zaleceniami The International Federation for Structural Concrete *(fib)*.