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Selected Mechanical Properties Analysis of Fibrous Composites Made on the Basis of Fine Waste Aggregate

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1. Introduction

The composites with dispersed reinforcement existed long before conventional reinforcement bars. Even before the birth of Christ people used various fibres such as animal dander or straw, mixing them with clay. The grounds for fibre reinforced concrete were laid by Joseph Lambot in the patent of 1847. Lambot suggested adding to the concrete fibres in the form of wires or nets (Naaman 1985). However, first use of steel components in concrete mix did not take place until year 1874, when A. Berard from California (USA) patented the strengthening of concrete by steel chips. In 1910 Porter was the first in the world to mention the possibility of using short steel wires in order to improve homogeneousness of concrete reinforced with only thick bars (Maidl 1995). The next patents, concerning various shapes of fibres and new methods of its application, were submitted as the first ones in the following countries by: H. Alfsen in France (1918), A. Kleinlogel in Germany (1920) and N. Zitkewic in England (1938). Yet, not until year 1963 in the USA, was elaborated the first theory of fine aggregate concrete containing steel fibres. The authors of the theory, J.P. Romualdi and G.B. Batson, proved that these steel fibres were able to inhibit development and propagation of cracks in concrete (Maidl 1995, Brandt 2008). This led to the possibility of introducing new technology of concrete reinforced with 25 mm fibres containing conventional fine aggregate. Guided by the rule that in fibre reinforced concrete the amount of small fraction aggregate should be dominant, this article presents the comparison of the results obtained from the study on fibrous composites containing waste aggregate with maximum granulation of 4 mm. There are many publications, in which SFRC made on the basis of waste sand was analyzed (Domski 2016, Głodkowska & Laskowska-Bury 2015, Domski 2015, Głodkowska & Kobaka 2013). However, these studies mostly concerned the typically selected volumetric quantity of steel fibres, i.e. 0.5, 1.0, 1.5, 2.0 and 2.5%. The presented analysis was conducted based on practical aspects of quantitative use of steel fibres. The analysis was limited to two composites, in which the volume of steel fibres was 0.42% (Domski 2016) and 1.20% (Głodkowska & Laskowska-Bury 2015), considered accordingly as minimal and optimal.

2. Characteristics of composite

Concrete is the most popular construction material in the world. The basic component for concrete is aggregate, which constitutes approximately ¾ of its volume. It is estimated that annual demand on aggregate is 3,000 kg per one person. Such a big use of aggregate significantly influences the natural environment. Furthermore, the aggregate deposits are not evenly spread out around the world. It is the reason why the grading curves for concrete (e.g. reference concrete according to EN 1766) are difficult to obtain without additional activity. The regions with deficiency of coarse aggregate are in a particularly difficult situation as they are at risk of increased environmental degradation. This is due to the fact that more all-in aggregate is needed to prepare aggregate for concrete (e.g. the reference one).

In the analyzed composites the used aggregate was sand of 4 mm granulation, which is a waste material in aggregate mines located in northern Poland. In this area a significant part of the output is subjected to the process of hydroclassification which results in obtaining 80% of sand and only 20% of coarse aggregate. This disproportion leads to the situation where most of sand remains unused in numerous plies located nearby the aggregate mines (Fig. 1). The postulate to somehow utilise remaining waste sand dumps constitutes a world-wide tendency consisted with Sustainable Ecological Development (Sadowska-Buraczewska

& Rutkowski 2013, Błaszczyński & Król 2015, Meyer 2009, Hendriks & Janssen 2003, Siddique 2008, Soares et al. 2014, Ulsen et al. 2013). The similar phenomena of excessive sand fractions can be observed in other parts of the world, e.g. in Middle East or in North Africa (Al-Harthy et al. 2007).

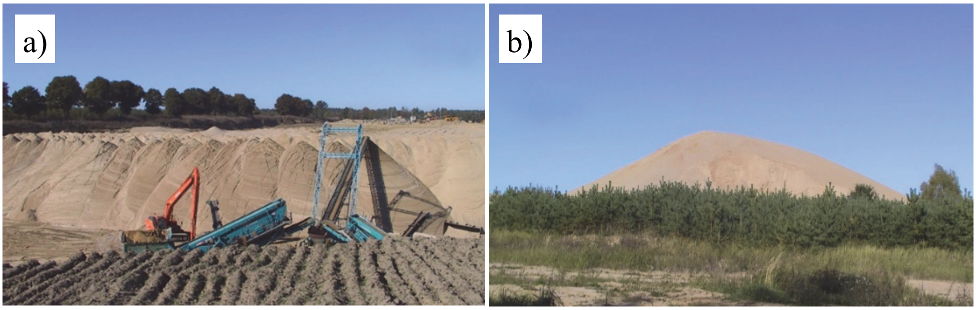

Fig. 1. Waste sand dumps in operative (a) and inoperative (b) aggregate mine (northern Poland area)
Rys. 1. Hałdy piasku w czynnej (a) i nieczynnej (b) kopalni kruszyw (obszar północnej Polski)

The figure 2 presents waste sand grading curves, appointed by various authors. These curves only insignificantly differ one from another, despite the fact that sand used in these studies originated all from various aggregate mines located in northern Poland. It proves that all these deposites are postglacial or fluvioglacial residues, developed in the same period. The used aggregates were additionally analyzed. Selected results are presented in table 1. Portland cements CEM II were used as binders in analyzed composites. Each cement mixture had different ash content. In case of cements of A-V series, the mixture was additionally sealed by silica dust (Głodkowska & Laskowska-Bury 2015). In every other analyzed composite, there was used a superplasticizer of FM series (Cartuxo et al. 2015). All composites were reinforced with steel fibres, which were 50 mm long and had 0.8 mm in diameter. Detailed analysis of the fibres is presented in (Katzer & Domski 2012). Figure 3 presents a histogram of tensile strength (R_m) of used steel fibres. The average value of strength, measured on 30 fibres, was 1155.2 MPa, and with standard deviation of 72.7 MPa. Described strength fits the range from 1153 to 1167 MPa, which is the range declared by the fibre producer. The conducted analysis confirms that the used fibres comply with tensile strength declared by the producer.

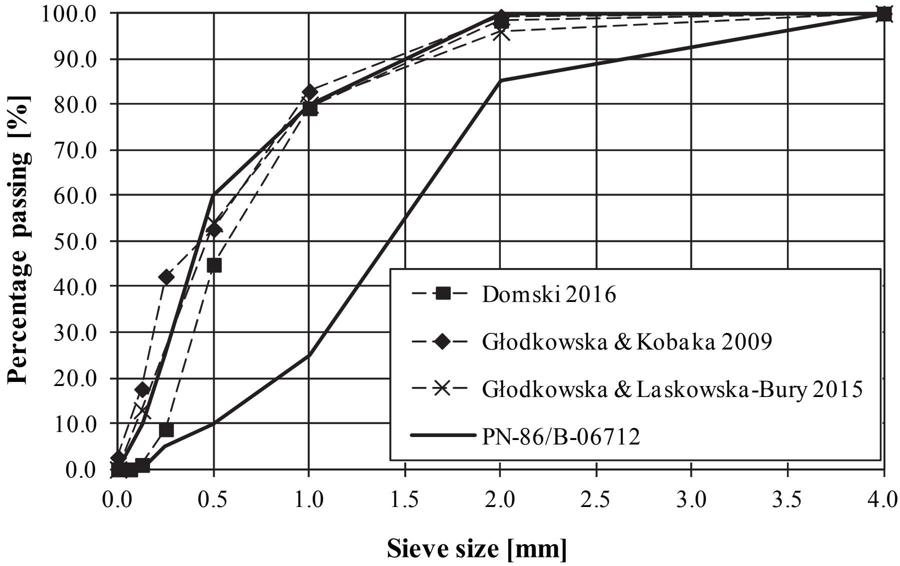

Fig. 2. Grading curves of waste aggregates
Rys. 2. Krzywe przesiewu kruszywa odpadowego

Table 1. Selected properties of waste aggregate
Tabela 1. Wybrane właściwości kruszywa odpadowego

Characteristics and origin of aggregate	Acc to (Głodkowska & Laskowska-Bury, 2015), mine in Lepino	Acc to (Domski 2016), mine in Sępólno Wielkie
Bulk density in loose state	1634 kg/m^3	1600 kg/m^3
Grain density	2632 kg/m^3	2600 kg/m^3
Quantity of mineral dust	1.3%	1.0%
Voids	32%	30%
Grain median	0.46 mm	0.28 mm
Foreign body content	0.0%	0.0%

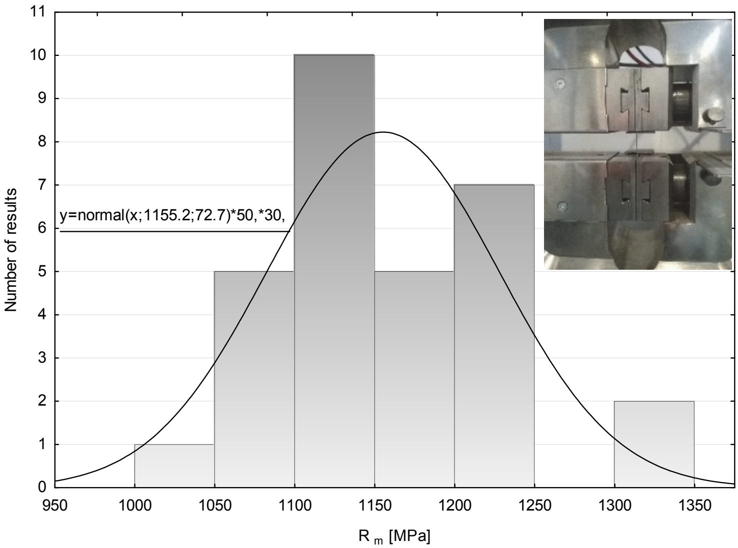

Fig. 3. Histogram of tensile strength and tensile strength test of steel fibres
Rys. 3. Histogram wytrzymałości na rozciąganie oraz badanie wytrzymałości na rozciąganie włókien stalowych

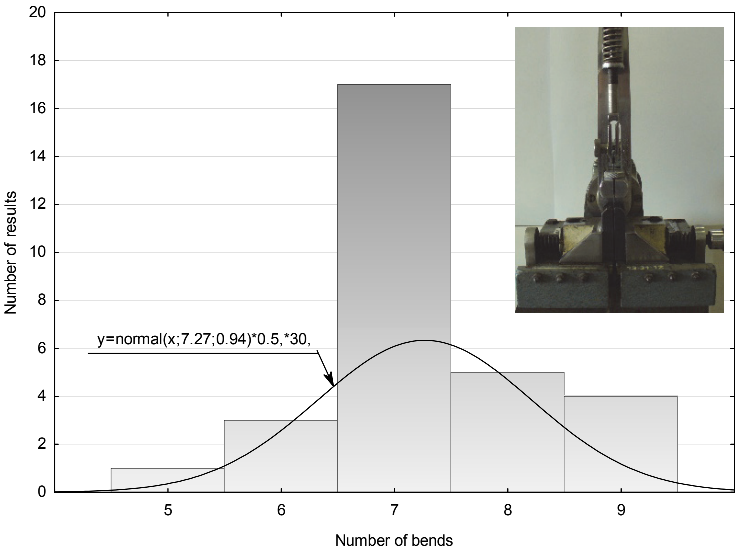

Fig. 4. Histogram of ductility and bend test of steel fibres
Rys. 4. Histogram odporności na przeginanie oraz badanie przeginania włókien stalowych

The fibres were also put to the bending test. It resulted in setting the number of bends necessary to break the fibres, accordingly to EN 10218-1:1994 (with reference to ISO 7801:1984 ''Metallic materials: Wire: Reverse bend test). Figure 4 presents results of the bends measurements and a general view on the work stand. The average number of bends measured on 30 fibres was 7.3 at standard deviation of 0.94. The producer declares that the fibres should be resistant to at least 7 bends. The test results indicate that the analyzed fibres comply with this number.

3. Mechanical properties of composites with fibres made on the basis of waste sand

Analyzing any concrete or composite, it is necessary to measure its strength properties (Bywalski et al. 2015, Domski & Katzer 2013, Domski et al. 2012, Seitl et al. 2010, Yazıcı et al. 2007, Chiaia et al. 2007, Naaman 2003). This is essential to be able to describe the usefulness of a concrete or composite in various applications. First, using the correlation between compressive strength and a number of used fibres, determined in (Głodkowska & Kobaka 2013), it was verified if it also describes the properties of analyzed composites. Figure 5 presents the relation between compressive strength measured on 150 mm cubes and the fibre content percentage (V_f). The conducted analysis shows that no composite fits in the curve proposed in (Głodkowska & Kobaka 2013). Because of this and due to the new results from (Głodkowska & Laskowska-Bury 2015) and (Domski 2016), the proper correction was made. The least-square method was used to determine the quadratic function, for which the correlation ratio is 0.87.

Another analyzed quality was tensile strength while cracking, tested on cubic samples of 150 mm. In this case it was considered, also based on the function described in (Głodkowska & Kobaka 2013), whether the results of analyzed composites fit in the proposed range (fig. 6). According to the analysis of the composite with 1.2% of fibre content, the results fit the range of the curve proposed in (Głodkowska & Kobaka 2013). However, the composite with 0.42% of fibre amount slightly deviates from the curve and this is why a new curve was suggested (fig. 6). It was measured with the least square method using the test results from (Domski 2016, Głodkowska & Laskowska-Bury 2015 and Głodkowska

& Kobaka 2013). The new curve shows that the correlation ratio of 0.94 is lower than in (Głodkowska & Kobaka 2013), but still relatively high.

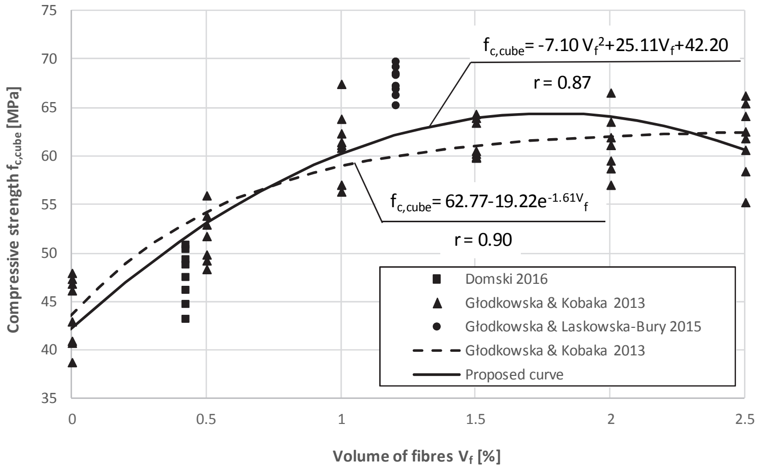

Fig. 5. Compressive strength vs. content of steel fibres
Rys. 5. Wytrzymałość na ściskanie w funkcji ilości włókien stalowych

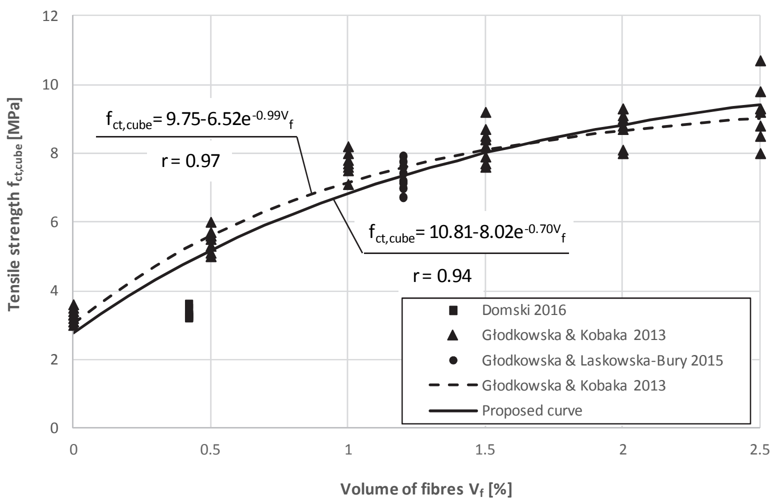

Fig. 6. Tensile strength at splintering vs. content of steel fibres
Rys. 6. Wytrzymałość na rozciąganie przy rozłupywaniu w funkcji ilości włókien stalowych

The study also included the analysis of modulus of elasticity. According to the literature (Naaman 1985, Maidl 1995, Brandt 2008, Głodkowska & Laskowska-Bury 2015, Błaszczyński & Przybylska-Fałek 2015), adding steel fibres to the composite results in a slight increase of static modulus of elasticity. Lack of significant influence of fibres on the modulus of elasticity can be caused by two factors. On the one hand, it can be caused by the increase of concrete compressive strength and on the other, by random setting of steel fibres and by the increase of air in hardened concrete (Rudzki et al. 2013, Bywalski & Kaminski 2011, Głodkowska & Kobaka 2012). Fig. 7 presents the relation between values of modulus of elasticity and compressive strength of several composites with fibres. These values were referred to the function presented in EN 1992-1-1. On the basis of this relation it can be stated that the function from EN 1992-1-1 does not describe variation of modulus of elasticity of tested composites. This is the reason why another function was proposed (fig. 7). It was set by the least-square method using test results from (Głodkowska & Kobaka 2009, Głodkowska & Laskowska-Bury 2015, Domski 2016). The correlation ratio for the proposed curve was 0.76.

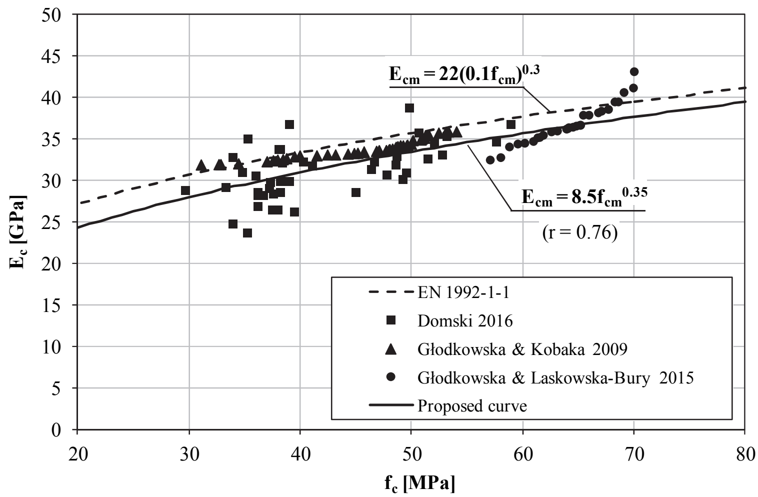

Fig. 7. Relation between modulus of elasticity and compressive strength
Rys. 7. Zależność pomiędzy modułem sprężystości a wytrzymałością na ściskanie

Figure 8 presents the relation between loading force and CMOD depending on the amount of steel fibres in concrete. Analyzing shape of each graph it can be stated that some composites, with steel fibres content of 0.42 and 1.20%, have the *pcs* attribute, i.e. decrease of destructive force together with increase of CMOD after the first crack appearance. On the other hand, for composites with steel fibre content of 0.90 and 0.50% the destructive force increases after appearance of the first crack. The test results of residual compressive strength clearly indicate on ductile nature of analyzed materials. It is caused by the fact that fibres significantly inhibit formation and expansion of cracks in composite with fibres. Thanks to applying dispersed reinforcement, composites are not so suddenly destroyed as it happens with ordinary concrete (Głodkowska & Kobaka 2012, Błaszczyński & Przybylska-Fałek 2015). Even the smallest amount of fibres, equal to 0.42%, comply with the minimal values of residual strength, specified in EN 14889-1 (1.5 MPa for COMD = 0.5 and 1.0 for CMOD = 3.5), which are declared by producers when their product contain adequate number of fibres (fig. 8 and tab. 2). Reaching these minimal values ($f_{R1,min}$ and $f_{R4,min}$) by every kind of steel fibres is essential for them to meet the assumed level of performance.

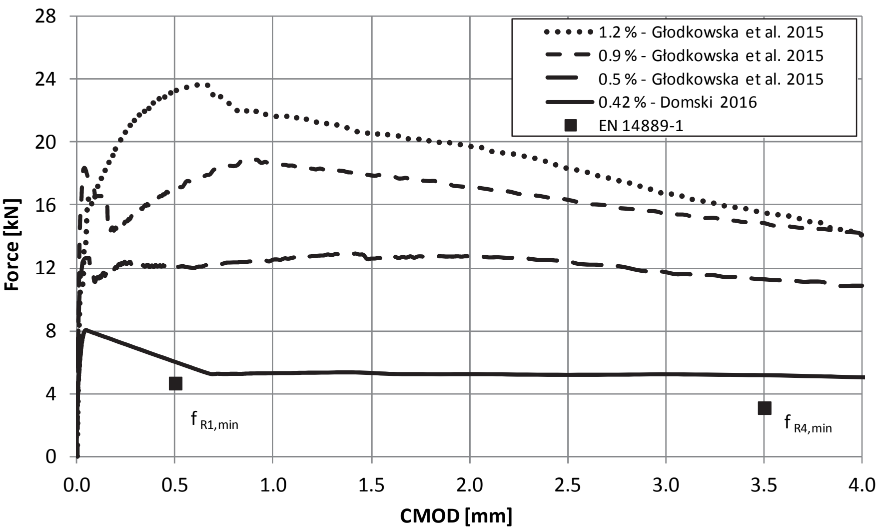

Fig. 8. Relation between loading force and CMOD
Rys. 8. Zależność pomiędzy siłą obciążającą a CMOD

Ultimately, based on fig. 8, the characteristic residual strengths were determined and the composites were classified given the proposal from Model Code 2010 (fib Bulletin 55 2010) (tab. 2). Classification 7b according to (fib Bulletin 55 2010, di Prisco et al. 2009) defines the analyzed material as composite with fibres (1.2%) of high f_{R1} value (range from 1÷8). The letter „b" in its name means that the composite has the *pcs* value, obtained from the f_{R3}/f_{R1} dependence („a" and „b" – *pcs*, „d" and „e" – *psh*).The composite with the level of fibre content of 0.42% reached the classification 2a. It can be presumed that there is a possibility of reaching even lower class (e.g. 1a). However, it should be noted that the obtained residual strength values are characteristic and should be reduced in case of designing bended and sheared construction elements.

Table 2. Average values of residual strength depending on the width of the opening crack (Głodkowska et al. 2015, Domski 2016)
Tabela 2. Średnie wartości wytrzymałości resztkowych zależne od szerokości rozwarcia rysy (Głodkowska i in. 2015, Domski 2016)

Crack mode opening displacement (CMOD) [mm]		0.5	1.5	2.5	3.5	f_{R3} – f_{R1}	Classification according to MC2010
Residual strengths [MPa]	1.20 [%]	7.45	6.55	5.85	4.95	0.78	**7b**
	0.90 [%]	5.45	5.72	5.23	4.75	0.96	**5c**
	0.50 [%]	3.38	4.04	3.99	3.62	1.18	**3d**
	0.42 [%]	2.39	1.43	1.41	1.40	0.59	**2a**
Residual strengths $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$ were determined for crack mode opening displacement (CMOD), equal respectively to: 0.5, 1.5, 2.5, 3.5 mm.							

4. Summary

The results of conducted analysis prove that mechanical properties of fine aggregate composites made of waste sand with steel fibre content ranging from 0.42% to 2.5% comply with the requirements imposed on structural materials (fib Bulletin 55 2010, di Prisco et al. 2009). As it arises from (Głodkowska & Laskowska-Bury 2015) the most optimal quantity of steel fibres is 1.2% of the composite volume. Of course, the proper type of composite can be chosen depending on the strain level of construction elements. Ultimately, thanks to their properties, the analyzed composites can constitute in some cases an alternative for classic concrete as well as the material for creating construction elements such as: foundation plates, floor slabs, beams or shells (Domski 2015).

The possibility of using waste sand as aggregate of full value in the process of producing construction materials on an industrial scale would largely resolve the problem of managing waste sand dumps located in northern Poland. Large amounts of fine aggregate, occurring in a form of industrial waste, could become the basic component of materials used to produce construction elements and thanks to that, they could be the new regional treasure (Domski 2016, Głodkowska et al. 2015, Głodkowska & Laskowska-Bury 2015, Głodkowska & Kobaka 2009).

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Analiza wybranych właściwości mechanicznych fibrokompozytów na bazie drobnego kruszywa odpadowego

Streszczenie

Prezentowany artykuł dotyczy ochrony środowiska w aspekcie ograniczania zużycia surowców naturalnych oraz emisji dwutlenku węgla. Swoją tematyką wpisuje się on w ogólnoświatową tendencję związaną z tzw. Zrównoważonym Rozwojem Środowiska. Obszary Polski północnej są ubogie w kruszywo grube, które jest niezbędne przy produkcji tradycyjnych betonów. W tej sytuacji, aby uzyskać pełnowartościowe kruszywo do betonów, należy przerobić znacznie większą ilość urobku w postaci pospółki, przy jednoczesnym zwiększeniu nakładu pracy i energii. W efekcie tych zabiegów uzyskuje się różne frakcje kruszywa, jednak w znacznej części, bo w ponad 80%, jest to piasek o uziarnieniu do 4 mm. Sytuacja ta sprawia, że w obszarze kopalń kruszyw, znajdują się liczne hałdy piasku, traktowane jako odpad poprodukcyjny.

Argumenty te skłoniły autorów niniejszego artykułu, aby zaproponować rozwiązanie zaistniałego problemu. Przeprowadzono analizę wyników badań piasku, pochodzącego z dwóch kopalń z obszaru Polski północnej, która obejmowała: krzywą przesiewu, ziarno mediana, gęstość nasypową w stanie luźnym, gęstość ziaren, zawartość pyłów mineralnych, jamistość oraz zawartość ciał obcych. Wyniki z przeprowadzonej analizy potwierdziły możliwość wykorzystania piasku jako kruszywa w kompozytach cementowych z dodatkiem włókien stalowych. Dodatkowo przeanalizowano uzyskane, w ramach wcześniej przeprowadzonych badań, właściwości mechaniczne wybranych haczykowatych włókien stalowych o średnicy 0,8 mm i długości 50 mm. Zweryfikowano uzyskane wytrzymałości na rozciąganie oraz liczbę przegięć z parametrami deklarowanymi przez producenta włókien. Zasadnicza analiza dotyczyła dwóch specyficznych fibrokompozytów o objętościowej zawartości włókien 0,42% i 1,2%, uznanych za minimalną i optymalną ilość włókien w mieszance. Dla tych kompozytów przeprowadzono analizę statystyczną obejmującą wytrzymałości na ściskanie i rozciąganie przy rozłupywaniu, moduł sprężystości i wytrzymałości resztkowe badanych fibrokompozytów. Na podstawie przeprowadzonej analizy zaproponowano krzywe opisujące zmianę wytrzymałości na ściskanie, wytrzymałości na rozciąganie przy rozłupywaniu oraz modułu sprężystości w funkcji ilości dozowanych włókien. Przedstawione funkcje dobrze charakteryzują zmienność wyżej wymienionych cech, o czym świadczy współczynnik korelacji, który zawierał się w przedziale od 0,76 do 0,94. Przeanalizowano również zależność pomiędzy siłą obciążającą a szerokością rozwarcia rysy (CMOD). Na jej podstawie możliwe było określenie wytrzymałości resztkowych, zaś zgodnie z ModelCode 2010, ustalono klasy fibrokompozytów oraz ustalono, czy możliwe jest częściowe zastąpienie zbrojenia tradycyjnego fibrokompozytem. Wyniki z przeprowadzonych analiz dowodzą, że właściwości mechaniczne drobnokruszywowych kompozytów wykonanych na bazie piasków odpadowych ze zbrojeniem rozproszonym odpowiadają wymaganiom stawianym budowlanym materiałom konstrukcyjnym.

Abstract

The presented article concerns environmental protection in terms of limiting consumption of natural resources and carbon dioxide emission. Its subject matter fits in the world-wide tendency consisted with Sustainable Ecological Development. Northern Poland area lacks of coarse aggregate, which is essential to produce ordinary concrete. In this case, in order to obtain wholesome aggregate to concrete production, it is necessary to process much more output in the form of all-in aggregate, increasing work and energy input at the same time. This procedure results in obtaining various aggregate fractions, however over 80% of it is sand with maximum granulation of 4 mm. As the result, most of sand remains unused in numerous piles located nearby the aggregate mines and is treated as post-production waste. These facts made the authors of the article to propose a solution of the existing issue. Therefore, there were analyzed the results of study on sand from two mines located in northern Poland. The analysis covered grading curves, grain median, bulk density in loose state, grain density, quantity of mineral dust, voids and foreign body content. The results of conducted analysis confirmed the possibility of using waste sand as aggregate in cement composites with steel fibres. Additionally, there were also analyzed the results of previous study on mechanical properties of selected hooked steel fibres, which were 50 mm long and had 0.8 mm in diameter. The tensile strength results and the number of bends, that were obtained, were verified with the parameters declared by fibre producers. The main analysis concerned two specific fibrous composites of volumetric content of fibres of 0.42% and 1.2%. These values are considered to be minimal as well as optimal for quantity of fibres in the mixture. In case of these composites, the statistical analysis also included compression strength and tension strength at splitting, modulus of elasticity and residual strength. On the basis of this analysis the curves were proposed describing value changes in compression strength, tension strength at splitting and modulus of elasticity in function of dosed fibres quantity. The presented functions well describe variability of aforementioned qualities, what is confirmed by correlation ratio, which was between 0.76 and 0.94. There was also analysed an interdependence between loading force and crack mode opening displacement (CMOD). On its basis it was possible to determine residual strength and to establish, according to Model Code 2010, fibrous composite classes and also whether it was possible to partially replace ordinary reinforcement with fibrous composites. The results of all these analysis prove that the mechanical properties of fine aggregate composites made on the basis of waste sand with dispersed reinforcement comply with the requirements imposed on construction materials.

Słowa kluczowe:
piasek odpadowy, kruszywo drobnoziarniste, kompozyt, włókna stalowe

Keywords:
waste sand, fine aggregate, composite, steel fibres