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Mechanical Characteristics of Green SCC Modified by Steel and Polymer Fibres

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1. Introduction

Concrete is the most popular building material all over the world. Its production is growing every year reaching globally the volume of 1m^3 per person [16]. At the same time production of concrete is associated with large energy and aggregate consumption. Such a huge resources and energy hungry production, affects natural environment in multiple ways. For years, researchers all over the world have been trying to make concrete production more green through using fly ash, slug, silica fume and other waste materials as partial substitutes of Portland cement. Another way of limiting the impact of concrete production on the environment has been harnessing waste aggregates (e.g. concrete or ceramic debris) instead of natural aggregates [8,12,13,19]. So far both research paths, have given limited solutions and there is still an urgent need for making concrete greener. The authors are convinced that the research effort should be expanded and also cover the processes of concrete casting and placement of reinforcement. Saving large amounts of energy during these technological steps would result in making the whole erected concrete structure much greener. Compacting fresh concrete mix through vibrating and laborious placement of re-bars and stirrups significantly increase the amount of energy needed for erecting a concrete structure. In the authors' opinion the solution for both problems is self-compacting concrete (SCC) reinforced with fibre. Using SCC one can avoid vibrating due to selfconsolidating and self-leveling properties of the mix [14,15,20,21]. Modifying SCC by adding engineered fibre would allow to resign from the majority or even all of traditional reinforcement [2,7,5,17,22,23].

2. Employed materials, mix design and curing

The SCC mix was prepared on the basis of natural fine aggregate characterized by "mediana grain diameter" (d_m) equal to 0.385 mm and density of 2.65 g/cm^3. The used coarse aggregate was in a form of two fractions of crushed basalt [9] 2–8 mm and 8–16 mm characterized by density equal to 2.95 g/cm^3. All three types of aggregate are presented in Fig. 1.

Fig. 1. Aggregates used in the research programme (photo by T. Ponikiewski) (from left: natural sand 0–2 mm, crushed basalt 2–8 mm, crushed basalt 8–16 mm)
Rys. 1. Kruszywa zastosowane podczas badań (fot. T. Ponikiewski) (od lewej: piasek 0–2 mm, łamany bazalt 2–8 mm, łamany bazalt 8–16 mm)

There was employed Portland cement CEM I 42.5 R as a binder and two admixtures (superplasticizer and stabilizer). The mix was additionally enriched by an addition of silica fume as microfiller influencing viscosity of the fresh mix. Tap water was the last ingredient. The detailed mix composition is presented in Tab. 1. There were used two types of fibre: steel hooked fibre and polymer fibre. Geometrical and mechanical properties of these types of fibre are presented in Tab. 2.

Table 1. SCC mix composition
Tabela 1. Skład mieszanki SCC

Ingredient	[kg/m^3]
CEM I 42.5	485
Natural sand (0 mm – 2 mm)	749
Coarse aggregate (2 mm – 8 mm)	467.7
Coarse aggregate (8 mm – 16 mm)	467.7
Water	203
Superplasticizer (3.5% of cement mass) – polycarboxylate	17
Stabilizer (0.3% of cement mass)	1.6
Silica fume (10% of cement mass)	48.5

Table 2. Geometrical and mechanical characteristic of used fibre
Tabela 2. Geometryczna i mechaniczna charakterystyka stosowanych włókien

Fibre	Length [mm]	Diameter [mm]	Cross-section	Tensile strength [MPa]	E [GPa]
Steel	20 ± 2	1.70 ± 0.17	rectangular	770 ± 115	210
Polymer	19	1	rectangular	615 ± 45	4

Specimens were cast in a form of cubes (150 mm • 150 mm •150 mm) and prisms (100 mm • 100 mm • 350 mm). All mixes were prepared in a rotary drum mixer. For the first 48 h the specimens were kept in their moulds tightly covered with polyethylene sheets. The specimens were then removed from their mould and cured in a water tank (temp.: +20ºC ± 2ºC) for the next 26 days.

3. Design of experiment and tested properties

The authors decided to harness one of the orthogonal designs of experiment. The choice of the design was made on the basis of previous experience of using different designs of experiment concerning fibre reinforced cement composites, which were described in previous publications [11,12].

The fibre types chosen for the research programme were coded as follows (X_1; X_2). Keeping in mind different specific gravity of steel and polymer, both fibre types were added to SCC mix, by volume. The object of the experiment was regarded as a complex material with an unknown structure which is unavailable for an observer and only the ‘input’ and ‘output’ parameters are known. The results of experiments were statistically processed. Values bearing the gross error were assessed on the basis of Dixon’s Q test [7]. The objectivity of the carried out experiments was assured by choosing the sequence of the realization of specific experiments from a table of random numbers. All calculations associated with specifying and graphic interpretation of the received mathematical model were carried out with the help of Statistica 10.10 computer programme. All presented plots were achieved by using a polynomial fit. Fitted functions are characterized by correlation coefficient equal to at least 0.80. The chosen experiment design was described in detail in Tab. 3.

Table 3. Experiment design
Tabela 3. Plan eksperymentu

Composite symbol	Reali-zation	X_1	X_2	V_{steel} [%]	$V_{polymer}$ [%]
1	5	-1.000	-1.000	0.0	0.0
2	3	-1.000	-0.333	0.0	0.3
3	15	-1.000	+0.333	0.0	0.6
4	11	-1.000	+1.000	0.0	0.9
5	6	-0.333	-1.000	0.5	0.0
6	1	-0.333	-0.333	0.5	0.3
7	16	-0.333	+0.333	0.5	0.6
8	8	-0.333	+1.000	0.5	0.9
9	9	+0.333	-1.000	1.0	0.0
10	7	+0.333	-0.333	1.0	0.3
11	13	+0.333	+0.333	1.0	0.6
12	12	+0.333	+1.000	1.0	0.9
13	4	+1.000	-1.000	1.5	0.0
14	14	+1.000	-0.333	1.5	0.3
15	2	+1.000	+0.333	1.5	0.6
16	10	+1.000	+1.000	1.5	0.9

There were tested properties of fresh SCC mix and properties of a hardened composites. Firstly, the density of fresh SCC mix was looked into. Then the consistency of the fresh SCC mix was tested using a slump-flow test conducted according to EN 12350 (Part 8). All properties of hardened composites were tested after 28 days of curing. The compressive strength was tested on cube specimens in accordance with PN-EN 12390-3. Other examined mechanical properties were tested using procedures described in ASTM C1018-97. This standard has been used for toughness tests of fibre reinforced cement composites for the last 15 years. According to this standard, the evaluation of composite toughness is based on dimensionless parameters of toughness indexes (I_5, I_{10}, I_{20} and I_{30}) and residual strength factors ($R_{10,5}$, $R_{20,10}$ and $R_{30,10}$). Some researchers have reservations about this standard testing procedure because it relates the evaluation of toughness indexes on precisely designated value of loading causing the appearance of the first crack [1,24].

Keeping in mind all the limitations of the procedure (including the fact that the standard was withdrawn in May 2006), authors decided to harness it as the most appropriate for the composites in question.

4. Achieved results

All achieved results were presented as contour plots. The density ρ of fresh SCC mixes varies from 2.39 g/cm^3 for unreinforced mix to 2.44 g/cm^3 for composite reinforced by $V_{f\ steel}$ = 0.75% and $V_{f\ polymer}$ =0.9%. The density is presented in Fig. 2. The slump flow diameter, as an indicator of consistency, varies from 60 cm for composite modified by maximum volume of both types of fibre, to 77.7 cm for unreinforced mix (Fig. 3). In Fig. 4 one can see results of compressive strength. The lowest values of $f_{c,cube}$ were achieved by the composite modified by the maximum volume of polymer fibre (less than 82 MPa). The highest compressive strength equal to 92 MPa was reached by the composite modified by steel fibre ($V_{f\ steel}$ = 0.75%). The first crack load varied from 8.6 kN for unreinforced mix to values exceeding 22 kN for composites with 1.5% addition of steel fibre (Fig. 4). Calculated residual flexural strength factors $R_{10,5}$ and $R_{20,10}$ are presented in Fig. 5 and 6. Equations modelling all tested and calculated properties are as follows:

$$\rho=2.388+0.052V_{f\ steel}+0.030V_{f\ polymer}-0.011\ V_{f\ steel}^2-0.044V_{f\ steel}V_{f\ polymer}+0.028V_{f\ polymer}^2$$

$$d=77.729+0,29V_{f\ steel}+15.481V_{f\ polymer}-0.715\ V_{f\ steel}^2-6.189V_{f\ steel}V_{f\ polymer}-28.192V_{f\ polymer}^2$$

$$f_{c,cube}=91.127+3.796V_{f\ steel}-21.714V_{f\ polymer}-2.879\ V_{f\ steel}^2+8.583V_{f\ steel}V_{f\ polymer}+10.719V_{f\ polymer}^2$$

$$P_{fc}=8.61-7.9678V_{f\ steel}+11.4202V_{f\ polymer}+6.3085\ V_{f\ steel}^2+0.0934V_{f\ steel}V_{f\ polymer}-10.826V_{f\ polymer}^2$$

$$R_{10,5}=-42.327+227.135V_{f\ steel}+165.438V_{f\ polymer}+53.008V_{f\ steel}^2-88.281V_{f\ steel}V_{f\ polymer}-120.705V_{f\ polymer}^2$$

$$R_{20,10}=-89.989+342.495V_{f\ steel}+402.972V_{f\ polymer}+1.556V_{f\ steel}^2-215.58V_{f\ steel}V_{f\ polymer}-235.639V_{f\ polymer}^2$$

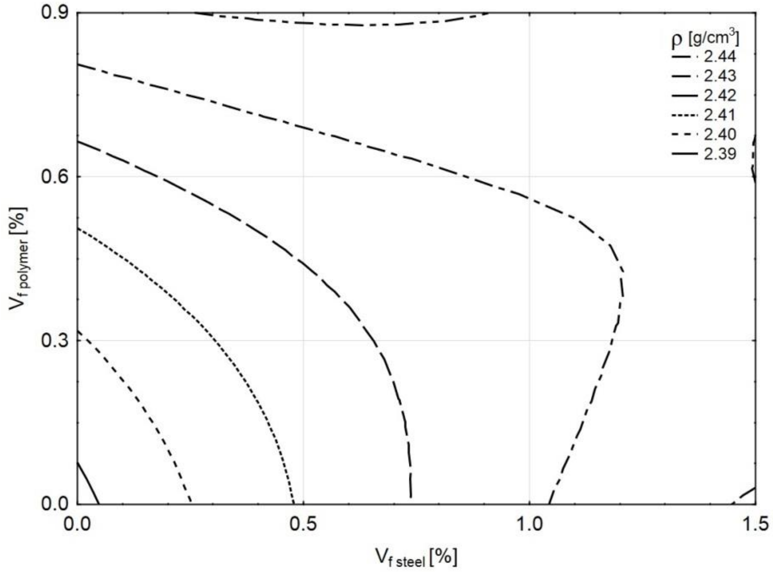

Fig. 2. Density of fresh SCC mix
Rys. 2. Gęstość świeżej mieszanki SCC

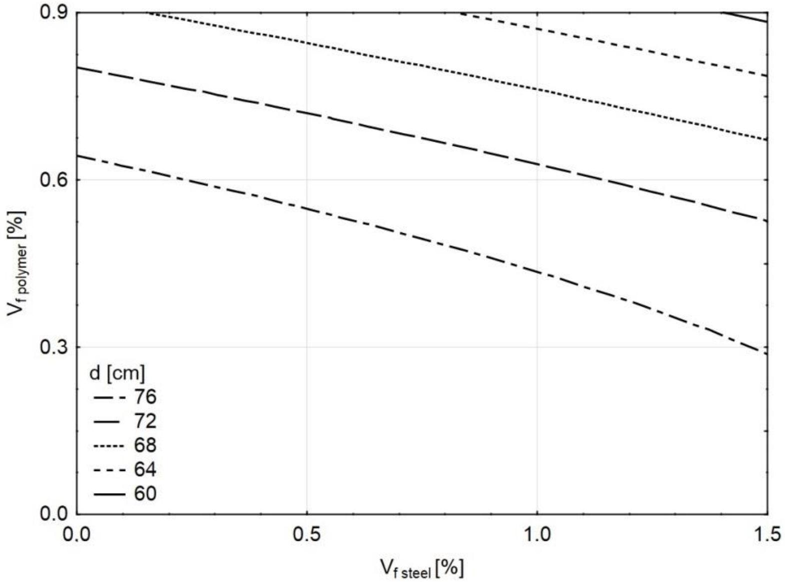

Fig. 3. Slump flow diameter
Rys. 3. Średnica rozpływu stożka Abramsa

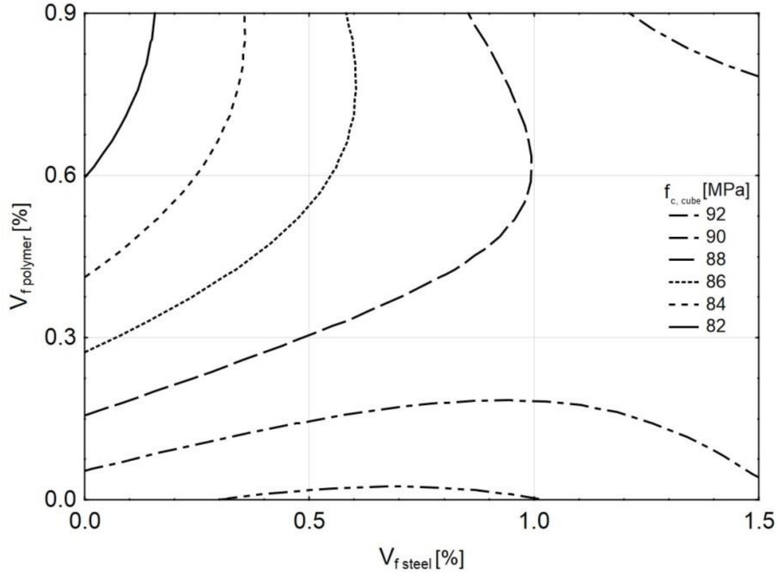

Fig. 4. Cube compressive strength
Rys. 4. Wytrzymałość na ściskanie

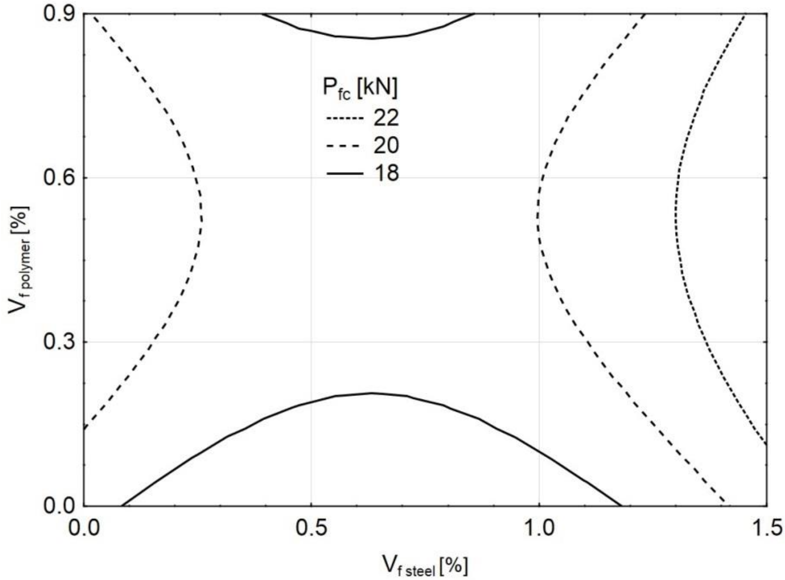

Fig. 5. First crack load
Rys. 5. Obciążenie, przy którym pojawia się pierwsza rysa

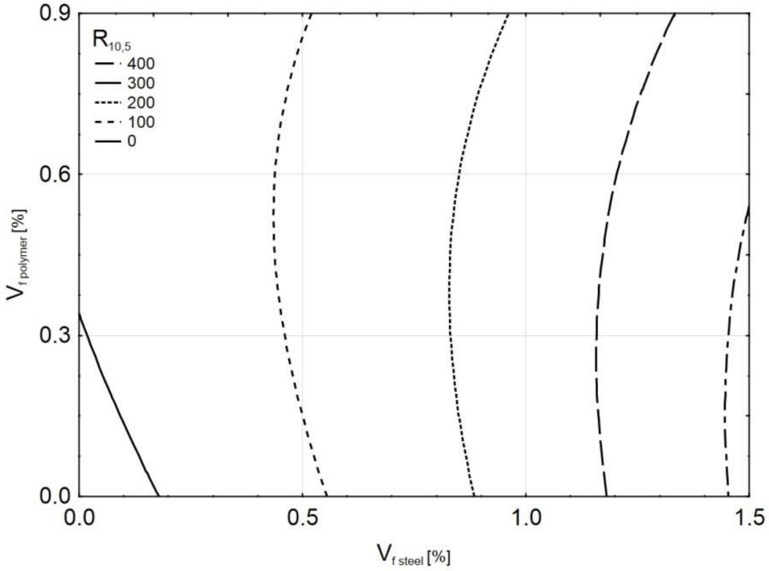

Fig. 6. Residual flexural strength factor $R_{10,5}$
Rys. 6. Wskaźnik rezydualnej wytrzymałości na rozciąganie przy zginaniu $R_{10,5}$

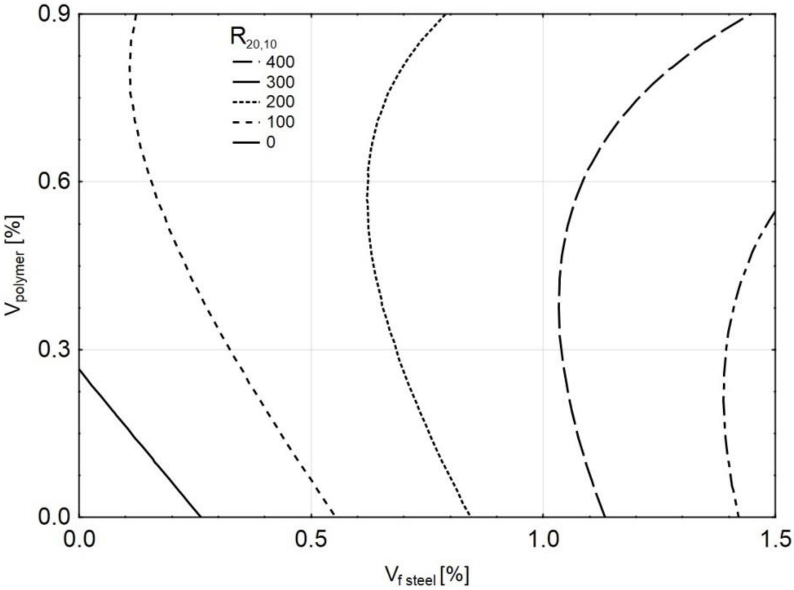

Fig.7. Residual flexural strength factor $R_{20,10}$
Rys. 7. Wskaźnik rezydualnej wytrzymałości na rozciąganie przy zginaniu $R_{20,10}$

5. Discussion

The conducted research programme has shown that creating SCC mix reinforced by steel and polymer fibre is feasible. Only mixes modified by 0.9% of polymer fibre and from 0.5% to 1,5% of steel fibre (composites 8, 12, 16) did not fulfil requirements of SCC in terms of fluidity. In case of these composites the slump flow test resulted in a mix not fully spreading after slump flow. The height of the remaining slump was equal to 9 cm, 10.5 cm and 12 cm respectively. Taking into consideration only properties of fresh mix, all composites with $V_{f\,polymer} \geq 0.6\%$. should be rejected.

All created SCC mixes were characterized by compressive strength allowing to associate them with C60/75 or C70/85 strength class according to EN 206-1. Compressive strength characteristics of SCC modified by steel and polymer fibre is similar to the characteristic of waste aggregate concrete tested in a previous research programme [12]. Strengths are much higher in case of SCC composites, but the general trend is similar. Both types of fibre significantly influence the compressive strength.

Residual flexural strength factors, which are presented in Fig. 6 and 7, show a very different trend from compressive strength. The dominant type of fibre addition influencing their values is steel fibre. The same relation was noticed while testing waste aggregate concrete [12]. These factors, though valuable from the testing point of view and material characteristics, are difficult to incorporate to a fibre composite designing procedure. Residual flexural strength factors can be implemented into serviceability limit states (SLS) analysis and ultimate limit states (USL) analysis [12].

The achieved results form an introduction to further research efforts, which should be focused not only on different types of steel and polymer fibre, but also on fatigue properties [10,25,26] and modelling of SCC reinforced by fibre under extreme loads [3,4]. Separate activities should be dedicated to environmental education of the end users of concrete mixes [18]. The results of this research programme indicate that there is future potential of SCC reinforced by fibre. This kind of composite could be used in a wide range of industrial and marine structures. Nevertheless, more tests are needed before starting full scale production of such composites.

6. Conclusions

The achieved results of the research programme prove that:

- it is possible to create stable SCC mix modified by a composition of steel and polymer fibre,
- to achieve stable SCC mix, the volume of polymer fibre must be limited to $V_{f\,polymer} \leq 0.9\%$,
- influence of steel and polymer fibre addition on mechanical properties of hardened SCC is similar to the influence of these fibre on ordinary concrete,
- mechanical properties of SCC reinforced by fibre allow to use it as a wholesome structural material,
- using SCC with fibres enables partial (in some cases full) substitution of traditional reinforcement (bars and stirrups),
- due to eliminating the need of compaction and reinforcement placement SCC with fibre is more environmentally friendly then ordinary concrete.

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Właściwości mechaniczne zielonych mieszanek SCC modyfikowanych włóknami stalowymi i polimerowymi

Strzeszczenie

W artykule przedstawiono program badawczy poświęcony wybranej grupie tak zwanych „zielonych" betonów które charakteryzują się wysoką przyjaznością dla środowiska naturalnego. W przypadku omawianego programu badawczego pod uwagę wzięto samozagęszczające się mieszanki betonowe (SCC) które dodatkowo modyfikowane były włóknami stalowymi i polimerowymi. Analizie poddano zarówno cechy świeżej mieszanki (konsystencja, gęstość) jak i stwardniałego kompozytu (wytrzymałość na ściskanie, obciążenie powodujące pojawienie się pierwszej rysy oraz wskaźniki rezydualnej wytrzymałości na rozciąganie przy zginaniu). Uzyskane wyniki pozwoliły określić przedziały optymalnego dozowania włókien oraz odnieść się do podobnych wyników uzyskanych przy badaniu zwykłych fibrokompozytów cementowych.

Słowa kluczowe: samozagęszczające się mieszanki betonowe, włókna stalowe i polimerowe, właściwości mechaniczne
Key words: self-compacting concrete mixes, steel and polymer fibres, mechanical characteristics