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THE USE OF RECYCLED CARBON FIBERS (rCF) IN PRODUCTION OF POLYMER CONCRETE TO IMPROVE MECHANICAL PROPERTIES

The recycling processes for CFRP waste are difficult due to their complex, and multi-material composition. Consequently, there is a need for new solutions to address this issue. The focus of CFRP composite recycling processes is primarily on recovering costly carbon fibers, which are characterized by exceptional mechanical properties. Pyrolysis has been identified as an effective method for the recovery of carbon fibers without significant damage. In this study, recovered carbon fibers (rCF) were used to produce polymer concrete. The fabricated polymer concretes contained carbon fibers of varying lengths (10, 20, and 30 mm) and volume fractions of 1 and 3%. The results showed that the addition of 3% post-pyrolytic carbon fibers resulted in significant improvement in the mechanical properties of the polymer concrete. Specifically, the flexural strength increased by more than 100% compared to the polymer concrete without carbon fibers, while the compressive strength improved by more than 60%. Overall, the study demonstrates that incorporating post-pyrolytic carbon fibers in the production of polymer concretes offers a promising solution to the challenge of CFRP waste. The use of these fibers not only helps in the recovery of valuable resources but also results in significant improvement in the mechanical strength of the final product.

Keywords: **carbon fibers, recycling, pyrolysis, polymer concretes, composites**

INTRODUCTION

Polymer composites represent a rapidly evolving field of research in the realm of engineering materials. The advanced properties of contemporary composites surpass those of traditional materials in terms of high mechanical strength coupled with low density. As a result, these materials find widespread applications in diverse industries such as construction, aerospace, transportation, and modern power generation, among others [1].

The incorporation of distinct phases with diverse properties is a fundamental aspect in the fabrication of polymer composites, as it enables the attainment of properties that are unachievable by individual phases alone. In cases where multiple reinforcing phases are employed, hybrid composites are generated. Nevertheless, the synergistic effects arising from the interaction between the constituent phases, and the resultant combination of material properties may pose challenges during the recycling processes [2, 3].

Despite their many difficulties, numerous methods of recycling polymer composites reinforced with carbon fiber have been developed to date. The basic methods of CFRP recycling are mechanical recycling [4], chemical recycling and thermal recycling [5, 6]. Owing to the set of beneficial properties of carbon fibers and their high price, recycling processes are focused primarily on recovery of the reinforcement material, excluding recovery of the matrix material. Currently, high hopes are placed on the recycling of CFRP in the pyrolysis process. Pyrolysis is carried out in an oxygen-free atmosphere in the temperature range of 400-700°C. The decomposition of the polymer matrix allows the recovery of gases and oils with high calorific value. The decomposition of the matrix leads to the release of the reinforcement material from the composite structure in a way that allows the preservation of high properties of carbon fibers without the loss of structural integrity [7-9].

Despite the knowledge of CFRP recycling methods, interest in reusing recycled carbon fibers is limited. The main limitation in their applicability is the heterogeneity of fiber properties after the recycling process. It may be beneficial to define areas that use the potential of carbon fiber properties, while accepting deviations in the mechanical properties of the recycled material. One of the most commonly used building materials is concrete, which is mainly made of cement (a binder), water and aggregate. The volume fraction of aggregates in concrete exceeds the proportion of cement and water. Most often, the concrete contains a fine aggregate, e.g. quartz sand, and a coarse aggregate, e.g. gravel. As an alternative to traditional unrestricted aggregates, it is possible to add waste, e.g. plastic waste [10], glass waste [11], fly ash waste [12] to the concrete structure, which may affect its properties.

The advantages of concrete are its ease of production, low price, ease of processing, and fire resistance. The most important disadvantages of concrete include water absorption, susceptibility to corrosion, low frost resistance, brittleness, low tensile strength and low thermal and acoustic insulation [13]. Because of the potential disadvantages of traditional concretes, its use in some application areas is limited. An alternative solution to traditional concretes with a cement binder can be polymer concretes, where the cement has been replaced with a synthetic resin [14].

Polymer concretes are characterized by better resistance to environmental conditions, including aggressive chemical agents and salt solutions, higher mechanical strength, frost resistance, low water absorption, and short curing time (short production time) [15, 16]. Many times the properties of polymer concretes are better than those of traditional concretes, which is why they displace cement-based concrete from some applications. A major limitation in the wide application of polymer concretes is their high price and more complicated production process. There are known concepts in which typical polymer concretes (without the addition of cement), traditional polymer-modified concretes (cement-polymer binder), polymer-impregnated concretes and surface-coated polymer concretes are produced [17].

This article attempts to use post-pyrolytic carbon fibers from recycled wind turbine blades in the production of epoxy polymer concretes. Quartz sand as a fine aggregate and gravel as a coarse aggregate were used to produce the polymer concretes. Chopped carbon fibers of various lengths and volume additions were added to the polymer concrete in order to increase the mechanical properties of the polymer concrete, especially the tensile strength.

EXPERIMENTAL PROCEDURE

The procedure for the recovery of carbon fibers from wind turbines in the pyrolysis process and the production of polymer concrete is presented in Figure 1. In the first stage, wind turbine blades were dismantled and transported to the place where the recycling process was conducted. The length of the recovered carbon fibers from the wind turbines is limited by the length of the semi-trailer in the truck and the dimensions of the pyrolysis reactor. The pyrolysis process was carried out at a temperature of 500-600°C in a non-oxidizing atmosphere (during the process, the atmosphere in the reactor gradually decreases in oxygen content, finally reaching a content of about 0%). Carbon fibers 3-8 m long with a partial epoxy residue on the surface were recovered. The pyrolysis process was carried out in such a way as to obtain fibers without significant damage or stiffness conditioned by the resin residue on the surface, which facilitates the subsequent process of mechanical cutting. The long carbon fibers were cut using a guillotine into lengths of 10 mm, 20 mm and 30 mm.

Seven series of polymer concretes were produced, the designations and composition of which are presented in Table 1. All the polymer concretes contain a 30% volume addition of epoxy resin acting as a binder for solid particles. Epoxy resin LH 288 (Havel Composites, Czech Republic) catalyzed by H505 (Havel Composites, Czech Republic) at a weight ratio of 100:27 was used to produce the polymer concretes. Gravel was used as the coarse aggregate and quartz sand as the fine aggregate. The volume ratio of gravel to sand is 4:3. Samples with different volume fractions of carbon fibers (1% and 3%) and different fiber lengths (10 mm, 20 mm and 30 mm) were produced.

TABELA 1. **Markings and composition of samples**

Sample	Coarse fraction (gravel)	Fine fraction (sand)	rCF		Epoxy resin
			length	volume fraction	
REF	40%	30%	-	-	30%
rCF_10_1%	39.5%	29.5%	10 mm	1%	
rCF_10_3%	38.5%	28.5%	10 mm	3%	
rCF_20_1%	39.5%	29.5%	20 mm	1%	
rCF_20_3%	38.5%	28.5%	20 mm	3%	
rCF_30_1%	39.5%	29.5%	30 mm	1%	
rCF_30_3%	38.5%	28.5%	30 mm	3%	

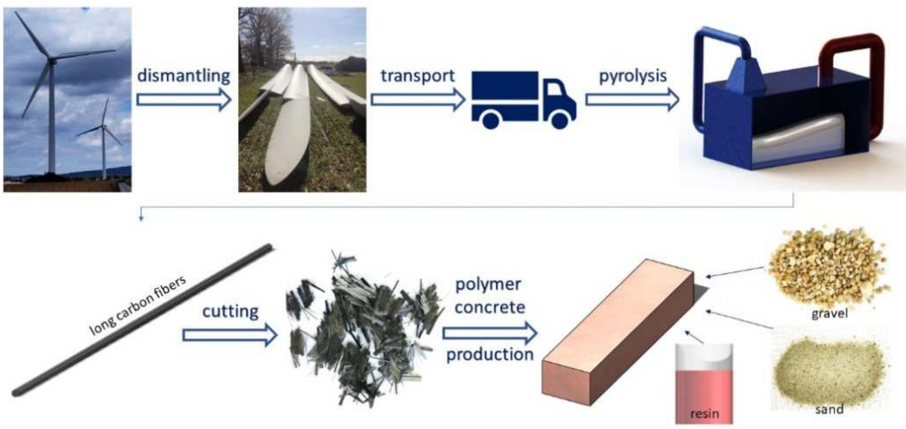

Fig. 1. Scheme of production of epoxy polymer concretes reinforced with carbon fiber from recycled wind turbine blades

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The aggregates (sand and gravel) were analyzed to determine the particle size distribution. For sand, the PSD analysis was carried out using the laser diffraction method by means of a Mastersizer 3000 particle size analyzer, and for gravel, a sieve analysis was performed utilizing a Multiserw LPzE-2e laboratory sieve shaker.

Figure 2 presents the aggregates used in the production of polymer concrete. The volume moment mean D [3, 4] for the sand is 449 µm. There was a dominant fraction of about (D50) 395 µm. In the case of gravel, about 90% of the grains are between 2 mm and 6 mm.

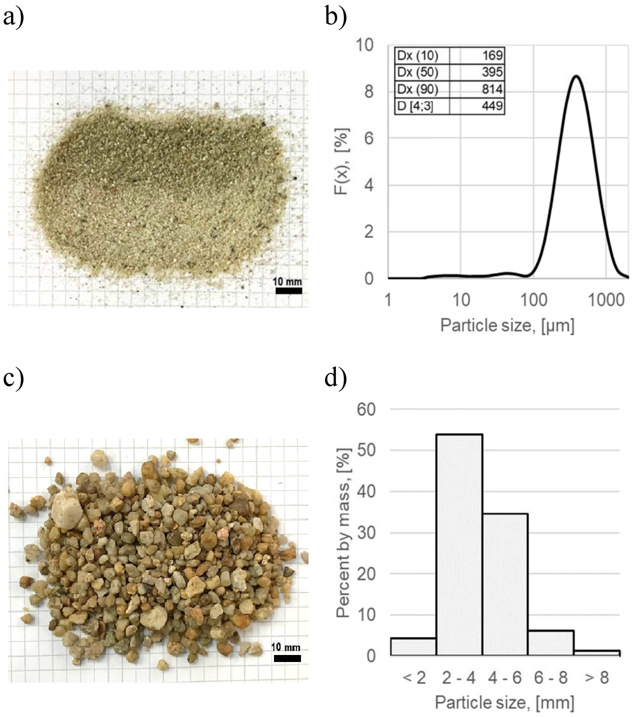

Fig. 2. Aggregates used in production of polymer concrete: a) fine fraction (quartz sand), b) PSD analysis of sand grains, c) coarse fraction (gravel), d) PSD analysis of gravel

The post-pyrolytic carbon fiber was observed by means of scanning electron microscopy using the SE technique on a Hitachi S-3400N device in order to describe the morphology of the fibers after the process and to detect resin residues on the fiber surface. The dry aggregates were mixed together and then the liquid epoxy resin was added. The mixture was homogenized using a mechanical mixer at 200 rpm for 5 minutes and then poured into silicone molds. Cross-linking was carried out at a temperature of about 25°C for 72 h, followed by post-curing at a temperature of 60°C for 12 h. Cylindrical samples with a diameter of 50 mm and a height of 100 mm were made for the compression test in relation to the standard for plastics PN-EN ISO 604:2006. Rectangular samples with a length of 200 mm, a width of 50 mm and a height of 25 mm were intended for the three-point bending test performed in accordance with the procedure of the PN-EN ISO 14125 standard.

RESULTS AND DISCUSSION

Figure 3 shows a single recycled carbon fiber of a wind turbine blade obtained in the pyrolysis process. The pyrolysis revealed residual resin on the surface of the carbon fiber, which allowed the structural integrity of the material to be preserved and prevented charring. The diameter of the pyrolysis fiber is 6.75 µm and it is estimated that the diameter did not change during recycling compared to the diameter of the virgin fiber used in the production of the wind turbine components.

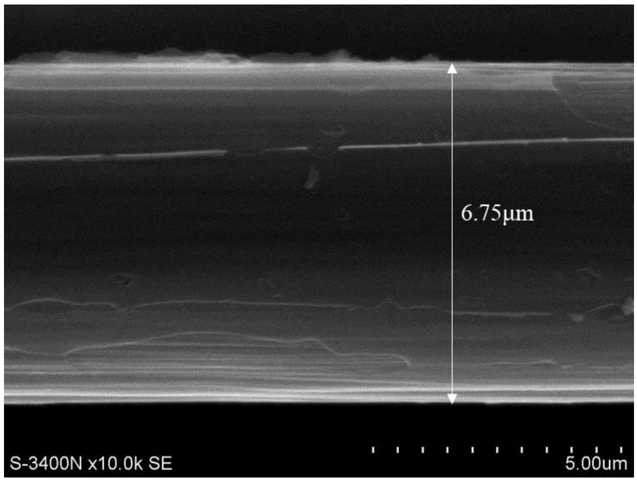

Fig. 3. Single carbon fiber obtained in pyrolysis process. SEM, SE technique, magn. × 10 k

Figure 4 presents the results of the three-point bending test of the polymer concretes. The reference polymer concrete sample (REF) has a flexural strength of about 20 MPa, and the addition of carbon fibers increases this value. Both the sample reinforced with 1% fibers with a length of 10 mm and the sample reinforced with 20 mm length fibers are characterized by no change in flexural strength, which may mean that the beneficial effect of composite strengthening was not achieved. Only carbon fiber with a length of 30 mm (at a 1% volume addition) raises the flexural strength to about 27 MPa, which means an increase of over 30% compared to the reference sample. A significantly better strengthening effect was observed in the polymer concrete reinforced with the 3% volume addition of carbon fibers (Fig. 4b). Fibers with a length of 10 mm lead to an increase in flexural strength by 34% (27.2 MPa), 20 mm, an increase by 44% (29.3 MPa), and for a length of 30 mm, an increase by almost 100% (40.3 MPa). The most favorable strengthening effect was achieved for the sample with the 3% volume addition of carbon fibers with the length of 30 mm. The introduction of higher volume additions and/or longer carbon fibers led to numerous problems in the homogenization and thickening of the mixture; therefore, it was considered to be the limit value for the conducted research.

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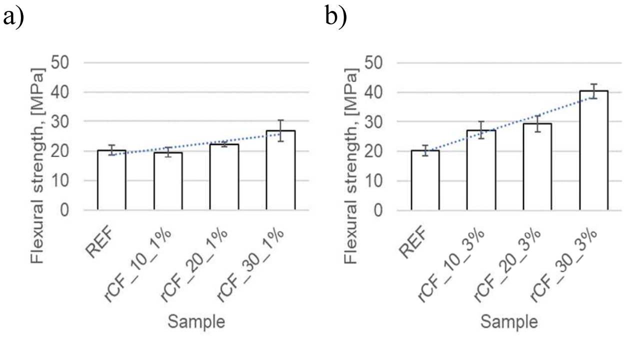

Fig. 4. Flexural strength of studied polymer concretes: a) for samples with 1% CF by volume, b) for samples with 3% CF by volume

Figure 5 displays the results of the compression test of the investigated polymer concretes. As in the case of flexural strength, growth in the compressive strength was observed with increasing volume additions of carbon fibers and their length. The compressive strength of the polymer concrete without the addition of carbon fibers is 50 MPa, which is a satisfactory value compared to traditional concrete. The addition of 1% by volume carbon fibers with the length of 10 mm raises the compressive strength to 68.5 MPa, 20 mm to 73.3 MPa, and for the length of 30 mm to 77.3 MPa (an increase by 53% compared to the reference sample). The addition of 3% by volume of carbon fibers leads to a greater rise in compressive strength than 1% by volume. In the case of the polymer concretes with the 3% CF addition (Fig. 5b), increases in the compressive strength by 21% for fibers with a length of 10 mm (61.2 MPa), by 43% for fibers with a length of 20 mm (72.6 MPa) and by 66% for fiber lengths of 30 mm (84 MPa) were observed. The mechanical tests demonstrate that the addition of carbon fibers increases the mechanical strength of the material.

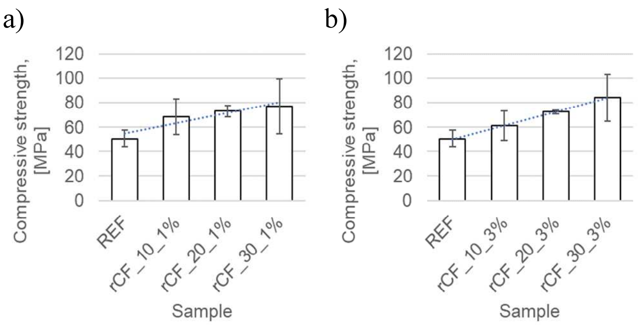

Fig. 5. Compressive strength of researched polymer concretes: a) for samples with 1% CF by volume, b) for samples with 3% CF by volume

Figure 6 shows the nature of the polymer concrete cracking depending on the length of the carbon fibers. The reference polymer concrete sample (REF) without the addition of carbon fibers cracks violently and disintegrates. The addition of carbon fibers prevents disintegration of the material during bending. The force acting on the material causes cracks, but the material maintains its integrity, which is extremely important for the safety of use when a structural element is damaged. The polymer concrete sample containing carbon fibers 30 mm long (Fig. 6c) is characterized by a crack propagating to half the height of the sample (at maximum strength), while the sample containing 10 mm fibers (Fig. 6b) has a crack along the entire height of the material.

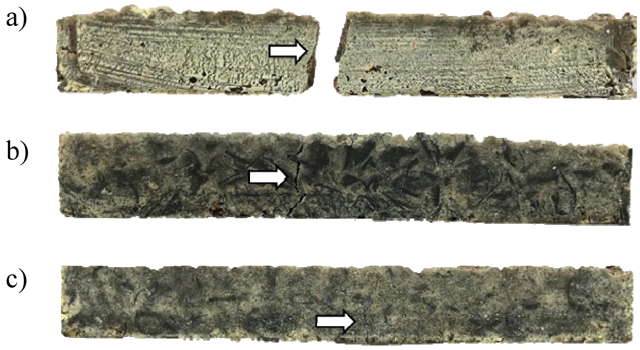

Fig. 6. Samples of polymer concrete after bending, arrow indicates crack: a) reference sample (REF), b) sample with 3% CF addition, length 10 mm (rCF_10_3%), c) sample with 3% CF addition, length 30 mm (rCF_30_3%)

In article [18], the influence of carbon fibers (20--30 mm long and 2% volume addition) on the mechanical properties of the reactive powdered concretes was investigated. It was shown that the concrete with the addition of carbon fibers had about a 12% higher compressive strength and flexural strength higher by about 28.5% compared to the concrete without the addition of carbon fibers. In [19], the influence of the carbon fibers (CF) on the mechanical properties and microstructure of coral concrete was investigated. Researchers will confirm the possibility of increasing the mechanical properties of concrete (compressive strength and tensile strength) by adding carbon fibers to a 2% content. It was found that the increase in the amount of carbon fibers with a length of 5 mm raises the compressive strength; in the case of the concrete with a strength of 20 MPa the growth was 17%, for concrete of 30 MPa by about 10% and for concrete of 40 MPa it was 11%. The tensile strength of the concrete is the most favorable for the amount of 1.5%, where in the C20 concrete the strength increased by 17%, in the C30 concrete by 14% and in the C40 concrete by 13% after 28 days. In publication [20], carbon fiber reinforced concretes (10 mm long) were tested with a volume fraction of 0.1-0.3%. The studies show that the additions of 0.1% and 0.3% do not cause a significant change in the compressive strength, and the intermediate addition of 0.2% leads to an increase in strength by about 6%. In article [21], a polymer concrete reinforced with carbon fibers with a length of 10 mm was examined, and the CF contents were 1% and 2% by weight. It was found that the addition of carbon fibers increased the compressive strength by about 16% compared to non-reinforced polymer concrete. An increase in the compressive strength from 36.1 to 55.1% was observed for the carbon fiber composite compared to the matrix and 85% higher strength compared to traditional concrete. Comparison of the literature data with the results of the obtained mechanical tests allows the conclusion to be drawn that the introduction of carbon fibers for reinforcing concrete is beneficial and increases the tensile strength and compressive strength. A greater increase in the mechanical properties after adding the carbon fibers is observed in polymer concretes, which is related to better adhesion of the resin matrix to the fiber surface and the final effect of composite strengthening.

CONCLUSIONS

The conducted research demonstrated that it is possible to use carbon fibers from recycled wind turbine blades. The employed pyrolysis process allowed the recovery of carbon fibers with an unchanged morphology compared to the virgin carbon fibers used for the production of the wind turbine components. The resin (matrix) remaining on the surface of the carbon fiber after the pyrolysis process allows partial preservation of the stiffness of the fiber, which is conducive to the processes of mechanical cutting of the fibers into shorter sections. Post-pyrolytic carbon fibers were used for the production of polymer concretes with the addition of gravel as the coarse aggregate and quartz sand as the fine aggregate. The conducted research allowed the following conclusions to be formulated:

– with the increase in the length of the carbon fibers, the flexural strength and compressive strength of the polymer concrete increase,
– the 3% volume addition of carbon fibers was set as the maximum due to difficult homogenization (the higher the fiber content, the more difficult the homogenization processes),
– the reference polymer concrete (without the addition of carbon fibers) has a flexural strength of 20 MPa and a compressive strength of about 50 MPa,
– it was found that the best properties of polymer concrete can be achieved using a 3% addition of carbon fibers with a length of 30 mm, then the flexural strength is about 40 MPa (an increase of 100% compared to the reference sample) and the compressive strength about 84 MPa (an increase of 66% compared to the reference sample),
– the addition of carbon fibers protects the material against disintegration at the time of cracking, which improves the safety of use, especially in the event of damage to the structure.

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REFERENCES

[1] Hsissou R., Seghiri R., Benzekri Z., Hilali M., Rafik M., Elharfi A., Polymer composite materials: A comprehensive review, Composite Structures 2021, 262, 113640.
[2] Jagadeesh P., Mavinkere Rangappa S., Siengchin S., Puttegowda M., Thiagamani S.M.K., Hemath Kumar M., Oladijo O.P., Fiore V., Moure Cuadrado M.M., Sustainable recycling technologies for thermoplastic polymers and their composites: A review of the state of the art, Polymer Composites 2022, 43(9), 5831-5862.
[3] Gonçalves R.M., Martinho A., Oliveira J.P., Recycling of reinforced glass fibers waste: Current status, Materials 2022, 15(4), 1596.
[4] Smoleń J., Godzierz M., Olesik P., Pawlik T., Kozioł M., Utilization of CFRP waste as a filler in polyester resin-based composites, Journal of Composite Materials 2021, 55(19), 2693-2701.
[5] Smoleń J., Olesik P., Jała J., Adamcio A., Kurtyka K., Godzierz M., Kozera R., Kozioł M., Boczkowska A., The use of carbon fibers recovered by pyrolysis from end-of-life wind turbine blades in epoxy-based composite panels, Polymers 2022, 14(14), 2925.
[6] Butenegro J.A., Bahrami M., Abenojar J., Martínez M.Á., Recent progress in carbon fiber reinforced polymers recycling: A review of recycling methods and reuse of carbon fibers, Materials 2021, 14(21), 6401.
[7] Abdallah R., Juaidi A., Savaş M.A., Çamur H., Albatayneh A., Abdala S., Manzano-Agugliaro F., A critical review on recycling composite waste using pyrolysis for sustainable development, Energies 2021, 14(18), 5748.
[8] Pimenta S., Pinho S.T., Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook, Waste Management 2011, 31(2), 378--392.
[9] Meyer L.O., Schulte K., Grove-Nielsen E., CFRP-recycling following a pyrolysis route: process optimization and potentials, Journal of Composite Materials 2009, 43(9), 1121--1132.
[10] Babafemi A.J., Šavija B., Paul S.C., Anggraini V., Engineering properties of concrete with waste recycled plastic: A review, Sustainability 2018, 10(11), 3875.
[11] Topcu I.B., Canbaz M., Properties of concrete containing waste glass. Cement and Concrete Research 2004, 34(2), 267-274.
[12] Nordin N., Abdullah M.M.A.B., Tahir M.F.M., Sandu A.V., Hussin K., Utilization of fly ash waste as construction material, International Journal of Conservation Science 2016, 7(1).
[13] Jamrozy Z., Beton i jego technologie, WN PWN, Warszawa-Kraków 2000.
[14] Bedi R., Chandra R., Singh S.P., Mechanical properties of polymer concrete, Journal of Composites 2013, 1-12.
[15] Kiruthika C., Prabha S.L., Neelamegam M., Different aspects of polyester polymer concrete for sustainable construction, Materials Today: Proceedings 2021, 43, 1622-1625.
[16] Laustsen S., Hasholt M.T., Jensen O.M., Void structure of concrete with superabsorbent polymers and its relation to frost resistance of concrete, Materials and Structures 2015, 48, 357-368.
[17] Bărbuţă M., Harja M., Baran I., Comparison of mechanical properties for polymer concrete with different types of filler, Journal of Materials in Civil Engineering 2010, 22(7), 696-701.
[18] Raza S.S., Qureshi L.A., Ali B., Raza A., Khan M.M., Effect of different fibers (steel fibers, glass fibers, and carbon fibers) on mechanical properties of reactive powder concrete, Structural Concrete 2021, 22(1), 334-346.

 All rights reserved

[19] Liu B., Guo J., Zhou J., Wen X., Deng Z., Wang H., Zhang X., The mechanical properties and microstructure of carbon fibers reinforced coral concrete, Construction and Building Materials 2020, 249, 118771.
[20] Song W., Yin J., Hybrid effect evaluation of steel fiber and carbon fiber on the performance of the fiber reinforced concrete, Materials 2016, 9(8), 704.
[21] Reis J.M.L.D., Mechanical characterization of fiber reinforced polymer concrete, Materials Research 2005, 8, 357-360.

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