Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2022, 71 (143), 56–63
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/518

Received: 30.06.2022
Accepted: 25.07.2022
Published: 30.09.2022

Mechanical properties of concretes modified with steel fibers and polypropylene

Paweł Helbrych
https://orcid.org/0000-0001-6907-0363

Czestochowa University of Technology, Faculty of Civil Engineering
69 J.H. Dąbrowskiego St., 42-201 Częstochowa, Poland
e-mail: pawel.helbrych@pcz.pl

Keywords: polypropylene fibers, steel fibers, fiber-reinforced concrete, concrete, mechanical properties
JEL Classification: L61, L65, L70

Abstract
This paper presents the effect of the addition of steel and propylene fibers on the mechanical properties of floor concretes (compressive and tensile strengths in the bending test). The polypropylene fibers used in the tests (fibrillated and single fibers) are dosed in the amount of 0.5 kg/m^3 to 2 kg/m^3, and the straight and hooked steel is dosed from 10 kg/m^3 to 25 kg/m^3. It is shown that, after 28 days of maturation, the highest compressive strength is achieved by concretes containing the addition of 25 kg/m^3 of hook-like steel fiber. In addition, the influence of the fiber content on the consistency of the concrete mix and workability is investigated. It was shown that the amount of steel fibers dosed in the tests, regardless of their shape, did not adversely affect the consistency and workability of the concrete mix. On the other hand, the addition of polypropylene fibers has a significant impact on the characteristics of the concrete mix. The addition of 2 kg/m^3 of polypropylene fibers caused the change of consistency from S4 to S1/S2 and worsened the workability of the mixture. All of the tested series of the concrete are created using the same technology. The concrete production technology reflects the concrete production technology for flooring concretes.

Introduction

Sustainable development is an idea that meets the needs of modern society, while not limiting the development opportunities of future generations. It is a concept that should be used in construction and the production of building materials (Ingaldi, 2015; Zhang et al., 2021; Tomov & Velkoska, 2022). According to the UN report, the construction industry is currently at a record level in terms of CO_2 emissions and the consumption of natural resources. One of the methods of reducing the use of natural resources in building production is the use of recycled materials (Pribulová, Futáš & Baricová, 2016). Despite the well-developed recycling techniques, the market for recycled concrete from C&D waste is developing slowly. It is influenced by its quality and price, which is estimated to be about 1–10% higher than in traditional concrete (Ma et al., 2022). In the production of recycled concrete, recycled aggregate is usually used as a replacement or additional to aggregate (Kim, 2022), and concrete floors from the production process use crushed concrete to acts as a partial replacement for the cement (Kim & Jang, 2022; Kim, Grabiec & Ubysz, 2022).

For the production of concretes, in laboratory tests, ash from the co-combustion of biomass and ash from the incineration of sewage sludge were used (Pietrzak, 2018b, 2019), which has been shown to not adversely affect the mechanical properties of the modified concrete. Waste polyethylene terephthalate from used bottles (PET) (Pietrzak, 2018a) was also utilized for the concrete modification, showing that a positive 5% of this waste as a cement substitute causes a slight decrease in the compressive strength of the concrete by around 3.5%, while it increases the bending strength of the concrete by about 3%. Concretes made in this way can be used in road infrastructure objects such as pavements or foundations.

In the article (Purcell et al., 2021), the authors investigated the effect of adding ground rubber from car tires to the concrete, ground rubber was added to the concrete mix as a substitute for fine aggregate in the amount of 0–10%, while maintaining the W/C ratio at 0.5. For samples with 2–4% of ground rubber, the compressive strength did not decrease in relation to the unmodified concretes, and the tensile strength slightly increased by 5%. For the production of the concrete, waste elastomer (TPE) was also used, ground to a fraction of 2–8 mm and employed as an aggregate substitute in the amounts of 2.5, 5.0, 7.5, and 10% of the cement specific mass (Ulewicz & Pietrzak, 2021). It was shown that the consumption of the addition of 2.5% thermoplastic elastomers did not adversely affect the structure of concrete and its mechanical properties, and the decrease in the strength after the frost resistance test did not exceed 20%. An extra advantage is the fact that the addition of 2.5% of the cement volume reduced the aggregate consumption by about 5% compared to the unmodified concrete.

For the production of concretes, fly ash from the combustion of sunflower-wood biomass in a fluidized bed boiler was used (Jura & Ulewicz, 2021). The research shows that the ash utilized for the tests can be added in the amount of 10–30% as a sand replacement (0–2 mm fraction) for the production of the composite materials with a cement matrix. The use of this additive in the range of 10–30% does not cause negative changes in the mechanical strength of the concretes in relation to the concretes without the additive, while reducing the consumption of sand in the concrete mix by about 15–20%. The work (Sharma, Sharma & Parashar, 2022) investigated the use of waste glass and demolition bricks as a replacement for coarse aggregate in the production of concrete, in which 0%, 25%, 50%, and 100% aggregates were replaced. Both the waste glass and the ground demolition brick were dosed on a weight basis. The samples were further tested after 28 days of the aging compressive strength was tested. The research showed that the workability of the concrete decreases with an increase in the amount of waste glass and ground demolition brick in the concrete mix, while compared to the control concrete, the addition of recyclates in the amount of 50% increased the compressive strength by 6%.

Studies have also been conducted on the effect of the addition of wastepaper to the concrete (Solahuddin & Yahaya, 2022). Two types of wastepaper were investigated: shredded used paper from a copier and cardboard. In both cases, fibers with a length of 40–47 mm were prepared from recyclates and dosed into concrete in the amount of 0%, 5%, 10% and 15%. After 28 days of aging, the specimens were subjected to a breaking tensile strength test. The tests showed that the addition of wastepaper to concrete in an amount of up to 10% increases the tensile strength when splitting, while the addition of a larger amount causes a decrease in this mechanical property. Moreover, it was observed that the addition of cardboard waste increases the tensile strength at splitting rather than the addition of recycled paper from photocopiers. The increase in strength in the tests compared to the control concrete amounted to 23%. By using waste materials for the cement production, it is not always possible to obtain concrete with the appropriate mechanical properties. Therefore, in order to increase the compressive and tensile strength of concrete and to limit cracks, fibrous additives are often added in laboratory tests in the form of polymer, steel, glass, or natural fibers (Makul, 2021).

The most commonly used fibers in the present day are steel fibers, which according to the standard (PN-EN 14889-1:2007) are straight or deformed fragments of cold drawn steel wire, straight, or deformed fragments of cut steel sheet, alloy fibers, chopped fibers, and rolled from steel blocks. The typical length of steel fibers ranges from 10–60 mm, the cross section is round, flat, or close to round, with a diameter of 0.2–1.5 mm. The most common shapes of the steel fibers used in modified concrete are straight, smooth, hook-shaped fibers with bends at both ends, as well as glued strands. According to the standard (PN-EN 14889-2:2007), polymer fibers are straight or deformed fragments of extruded, oriented, and cut polymer material, used to make a homogeneous concrete mix. Polymer fibers are added to the concrete in the form of short, thin threads (up to 30 mm) with a small diameter (0.02–0.05 ± 0.005 mm) or stiff rods with a diameter (0.2–0.5 ± 0.05 mm) and length up to 60 mm. Polypropylene, polyethylene, polyester, nylon, polyacrylic, or aramid are most commonly used to make polymer fibers (Latifi, Biricik & Mardani Aghabaglou, 2022).

The research (Helbrych, 2021) examined the influence of polypropylene fibers on the mechanical properties of concrete. Fibers with a length of 50 mm and a diameter of 1.2 mm were used in the tests, the results indicated that the optimal addition of polypropylene fibers for the laying method and technology assumed in the work was 1 kg/m^3. The results of compressive strength in relation to the control series increased by around 5%, and the tensile strength in the bending test by about 21%. In this study, we assess the influence on the mechanical properties of concretes of two other types of polypropylene fibers (fibrillated and single) of similar length (i.e., 50 mm) but different diameters and structure, compared to concretes with the addition of steel fibers (straight and hook-shaped), in the context of the same technology of the concrete mix production.

Research materials and methodology

The aim of this study was to identify the effects of dosing fibers made of various materials (steel and polypropylene) in concrete in the context of mechanical strength, and to assess the impact of fiber addition on the properties of the fresh mix such as consistency and workability.

Materials

Polypropylene fibers in the form of a twisted bundle of white color were used for the tests (Figure 1). They are 50 mm long (±1.5 mm), fibrillated, and marked as P1, while polypropylene fibers in the form of a monofilament were approximately 0.7 mm in diameter and 50 mm (±1.5 mm) in length, and marked as P2. The properties of polypropylene fibers are shown in Table 1.

In addition, the non-galvanized steel reinforcement was used for the tests (Figure 2) in the form of a straight and hooked wire. The two types of steel fibers used in this research were made of the same steel with a tensile strength of 1000–1020 MPa.

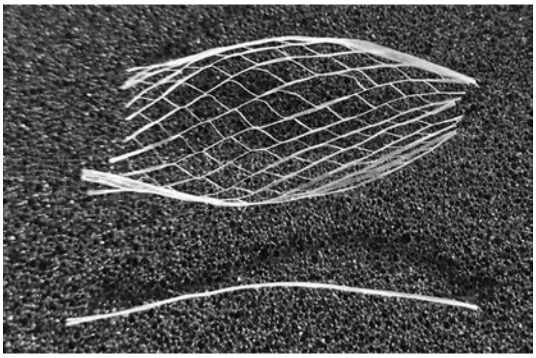

Figure 1. Polypropylene fibers used in the tests (P1 fiber above, P2 below)

Table 1. Properties of the used polypropylene fibers

Properties	Unit	P1 fibers	P2 fibers
Type of polymer	–	polypropylene	polypropylene
Density	g/dm^3	0.91	0.91
Diameter	mm	1.5	0.7
Length	mm	50	50
Elastic modulus	kN/mm^2	2	2
Tensile strength	N/mm^2	600	600
Ignition temperature	°C	160	160
Melting temperature	°C	160	160

They had the same 50 mm length, slenderness, cross section, and diameter. Straight fibers are marked as S1 and hooked ones as S2. Table 2 presents the geometric parameters of the fibers and their properties.

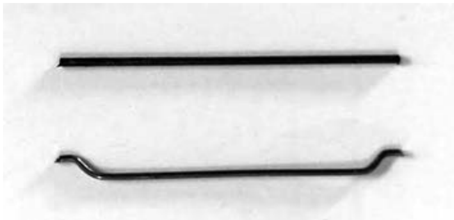

Figure 2. Steel fibers used in the tests (S1 fiber on top, S2 fiber on the bottom)

Table 2. Properties of the used steel fibers

Properties	Unit	S1 fibers	S2 Fibers
Fabric	–	steel	steel
Length	mm	50	50
Diameter	mm	1.2	1.2
Slenderness	L/d	41.6	41.6
Shape	–	straight	hook-like
Tensile strength	MPa	1000–1020	1000–1020
Elastic modulus	GPa	210	210

The concrete mix was made of generally available ingredients: CEM II 42.5R Portland cement, 2–8 mm and 8–16 mm gravel mix, 0–2 mm fraction sand, and tap water from the Czestochowa intake. The MasterEASE 5051 superplasticizer was also dosed into the concrete mix in the amount of 2.5% of the cement mass. Concrete was designed using the analytical-experimental method according to the study (Jamroży, 2020). Based on a literature analysis, among others (Glinicki, 2010; Pikus, 2016; Bentur & Mindess, 2019; Do & Lam, 2021), the W/C ratio = 0.45 and consistency class S4 were selected and the graining curve of the aggregate mixture was employed, so that it would fit in the upper field of the graining boundary curves (Glinicki, 2010; Jamroży, 2020). Concrete class C35/40 was designed; the recipe of the concrete mix is presented in Table 3.

Table 3. Recipe of the concrete mix

Type of the ingredients	Amount of ingredients per 1 m^3 of the mixture [kg]
Cement CEM II 42.5R	457.6
Water	205.9
Sand 0–2 mm	962.5
Gravel 2–8 mm	552.1
Gravel 8–16 mm	665.5
Superplasticizer	11.4
W/C	0.45
Consistency class	S4

Methodology

The dosing of all of the components of the concrete mixture was conducted by weight, in exactly the same sequence in all of the test series. The concrete mix manufacturing procedure was based on the information obtained from a local concrete plant, so that it corresponded to the industrial method of producing concrete mixes used for industrial floors. The technology of producing the concrete mix was the same for all test series. Started with dosing 50% fine aggregate (2–8 mm fraction) and coarse aggregate (8–16 mm fraction) into the mixer together with 50% sand, and the components were mixed for 1 min. The next step was adding 100% water to the mixer with the addition of 100% superplasticizer, the ingredients were mixed for 2 minutes. Then, the remaining parts of the aggregate were dosed (50% gravel of fraction 2–8 mm and 50% gravel of fraction 8–16 and 50% sand) and mixed for 2 minutes. Finally, the correct amount of fibers was dispensed. The time for mixing the concrete mix with the fibers was 2 minutes for all the series. The control series (SK) did not contain fibers. After the mixture was made, its consistency was checked each time using the drop cone method in g (PN-EN 12350-2:2019-07). 17 test series were carried out, each series consisted of at least 6 samples (3 with dimensions 150×150×150 mm and 3 with dimensions 150×150×600 mm). A summary of the series, and the number of fibers, is presented in Table 4.

The homogeneous concrete mix was laid in two layers in previously prepared forms consistent with (PN-EN 12390-1:2021-12). Each layer was vibrated for 20 seconds. The procedure of forming the test samples was in accordance with (PN-EN 12390-2:2019-07). After 24 hours, the samples were removed from the molds and stored in water at 20 ± 2°C until the tests. 28 days after the samples were made, the compressive strength tests were carried out according to (PN-EN 12390-3:2019-07) and the tensile strength of the concrete was found via a bending test – involving a freely supported beam symmetrically loaded with one force according to (PN-EN 12390-5). All of the tests were performed on a Toni Technik type 2030 testing machine that complies with the requirements (PN-EN 12390-4:2020-03).

Table 4. List of the test series

Series name	Type of fibers to be added	Number of fibers per 1 m^3 of the mixture [kg]
SK	–	–
P1-S1	P1 polypropylene	0.5
P1-S2	P1 polypropylene	1.0
P1-S3	P1 polypropylene	1.5
P1-S4	P1 polypropylene	2.0
P2-S1	P2 polypropylene	0.5
P2-S2	P2 polypropylene	1.0
P2-S3	P2 polypropylene	1.5
P2-S4	P2 polypropylene	2.0
S1-S1	S1 steel	10
S1-S2	S1 steel	15
S1-S3	S1 steel	20
S1-S4	S1 steel	25
S2-S1	S2 steel	10
S2-S2	S2 steel	15
S2-S3	S2 steel	20
S2-S4	S2 steel	25

Research results and discussion

For each test series, the consistency was checked using the drop cone method according to (PN-EN 12350-2:2019-07); the average values of the results are presented in Table 5. The highest cone slump was recorded for the samples from the control series (SK). For the series with polypropylene fibers, changes in the consistency from S4 to S1/S2 class were observed with the addition of progressively increasing amounts of fibers. No change in the consistency was observed in the series with the addition of steel fibers. The lowest average cone drop was recorded for series P2-S4, which was 45 mm.

For each series, 3 samples were made in the shape of cubic cubes with dimensions of 150×150×150 mm and the compressive strength

Table 5. List of the consistency classes of the tested concrete mixtures

Series name	Drop cone [mm]	Consistency class:
SK	190	S4
P1-S1	170	S4
P1-S2	150	S3
P1-S3	110	S3
P1-S4	70	S2
P2-S1	160	S4
P2-S2	120	S3
P2-S3	90	S2
P2-S4	45	S1/S2
S1-S1	190	S4
S1-S2	180	S4
S1-S3	165	S4
S1-S4	160	S4
S2-S1	190	S4
S2-S2	170	S4
S2-S3	160	S4
S2-S4	140	S3

(PN-EN 12390-3:2019-07) test was carried out in accordance with the standard on a Toni Technik machine type 2030. The load was increased at the rate of 0.5 MPa/sec. The averaged test results are presented in Figure 3, in which the standard deviation was calculated for each run.

The average compressive strength of the test concrete (SK), determined after 28 days, was f_{cm} = 50.80 MPa. For the series of concretes with the addition of P1 and P2 dispersed polypropylene reinforcement with a length of 50 mm, depending on the amount of dosing, it was 49.7 MPa (P1-S1 series) to 54.8 MPa (P2-S3 series). The standard deviation for all of the series was within the range from ±0.06 MPa for the P2-S4 series to ±0.61 MPa for the P1-S4 series. For the series of concretes with the addition of steel dispersed reinforcement S1 and S2 with a length of 50 mm, the average compressive strength was, depending on the amount of dosing, from 51.80 MPa (series S1-S1) to 65.70 MPa (series S2-S4). The standard deviation for all series was in the range from ±0.14 MPa for the S2-S1 series to ±0.39 MPa for the S2-S1 series.

The compressive strength results show that the compressive strength increases with an increase in the amount of fibers in the concrete mix. In the case of the polypropylene fibers used in the tests, the optimal compressive strength results were obtained in series with the addition of 1.5 kg/m^3 of fibers, above this value a slight decrease in compressive strength was observed. This phenomenon may depend on the method of positioning the mixture in the mold and the length of the vibrating time (in the tests, the mixture was placed in two layers and vibrated after 20 seconds). Moreover, a difference in the compressive strength in concretes with the addition of P1 and P2 fibers was observed. The lower strengths of the series with the addition of the P1 fibers may be related to the fiber structure. The fibrillated fibers did not develop into a distinct mesh in the mix, in particular in the series where they were dosed in larger

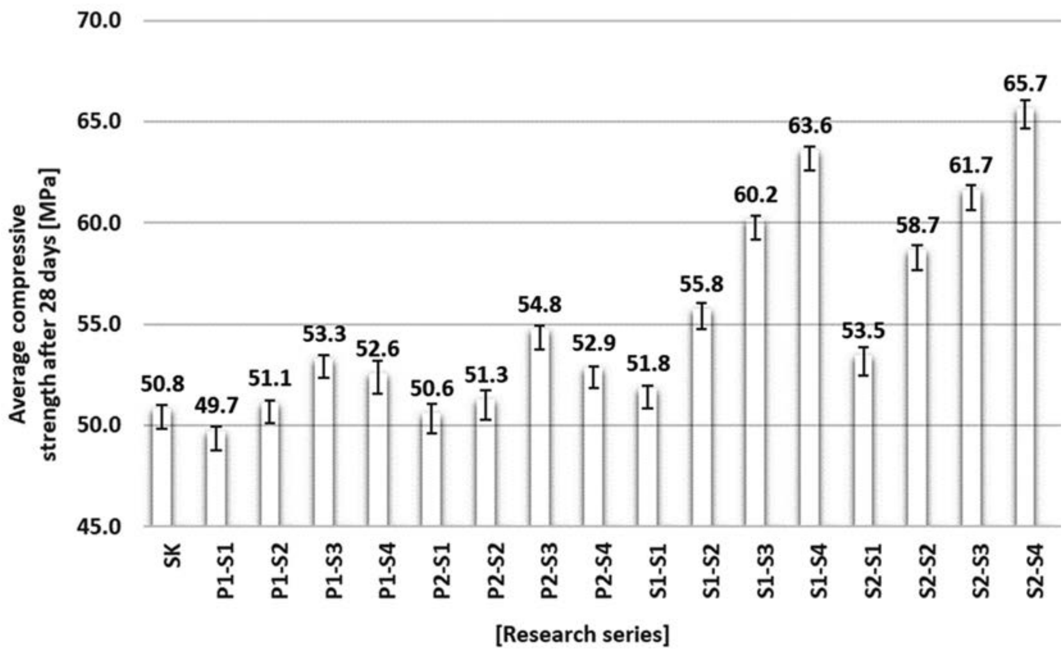

Figure 3. Compressive strength of the concretes of the tested series

amounts (P1-S3 and P1-S4), in which they usually kept their original form. The observations during the mixing showed that the monofilaments were better distributed in the concrete mix.

For each series, 3 samples in the shape of cubic cubes with dimensions of 150×150×600 mm were made, and the concrete tensile strength was tested in a bending test – the free-supported beam was symmetrically loaded with one force according to (PN-EN 12390-5) on a Toni Technik machine type 2030. The load was increased at the rate of 0.5 MPa/sec. The averaged test results are presented in Figure 4.

The average bending strength of the test concrete (SK), determined after 28 days, was f_{ct} = 4.2 MPa. For the series of concretes with the addition of P1 and P2 dispersed polypropylene reinforcement with a length of 50 mm, depending on the amount of dosing, it was 4.3 MPa (P1-S1 series) to 4.9 MPa (P2-S3 series). The standard deviation for all of the series ranged from ±0.04 MPa for the P2-S1 series to ±0.14 MPa for the P2-S2 series. For the series of concretes with the addition of steel dispersed reinforcement S1 and S2 with a length of 50 mm, the average bending strength was from 4.7 MPa (S1-S1 series) to 5.8 MPa (S2-S4 series), depending on the dosing quantity. The standard deviation for all series was within the range from ±0.02 MPa for series S2-S3 to ±0.11 MPa for series S1-S2.

The concrete tensile strength in the bending test – involving a freely supported beam symmetrically loaded with one force according to PN-EN 12390-5 – showed that with the increase in the amount of fibers in the mixture, the concrete tensile strength in the bending test increases. When considering the series of concretes with the addition of steel fibers, the series with the addition of hooked fibers (S2) achieved slightly improved results, which is related to the geometry of the fiber, and results in improved anchoring in the concrete. As in the case of the compressive strength test, in the series with the addition of P2 fibers (non-fibrillated), the results were slightly better than in the case of concretes with the addition of P1 fibers (fibrillated). Moreover, in the series with the addition of 2 kg/m^3, a slight decrease in the tensile strength of the concrete in the bend test was observed.

Modification of the concretes with fibers is a good method for improving the plastic properties of the composite. The fiber content in the concrete means that it does not deteriorate as rapidly as in the case of unmodified concretes. In the compressive strength tests, samples with the addition of fibers, after the test, were more similar to their form before the test. In the case of stretching, the effect of fibrous additives is more noticeable (with an increase in strength by almost 40%). The nature of the change in damage means that the sample does not break into two parts. After a crack has formed, specimens with the addition of fibers can still bear the specified loads until the cracked parts separate. It should be noted that, for each type of the dispersed reinforcement, there is a limit to the amount of addition to the mix, which should not be exceeded due to workability issues, as well as the difficulty of obtaining homogeneity and the possibility of optimal compaction.

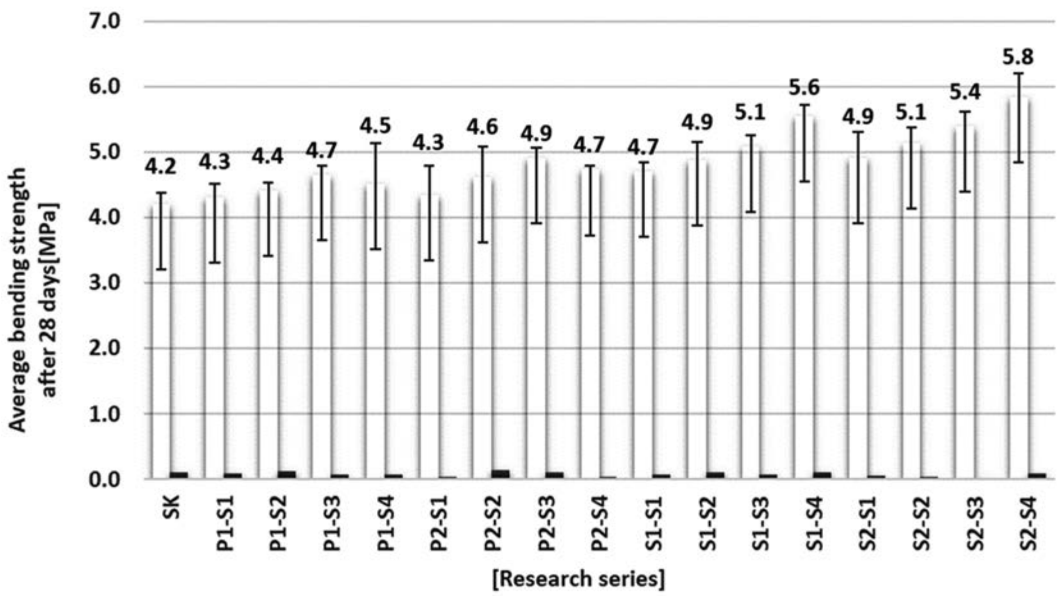

Figure 4. Tensile strength of the concrete in the bending test, which involved a freely supported beam that is symmetrically loaded with one force

The effectiveness of the concrete modification with the steel fibers is guaranteed by the adherence to technological regimes, since the material properties of this type of concrete largely depends on the homogeneity of the mixture and the degree of its compaction. Depending on the type of fibers used, the technology of making, embedding, and caring for the concrete mix should be selected appropriately. In the case of polypropylene fibers used in the tests, the optimal amount in the mixture, while maintaining the technology of production compliant with the tests, is 1.5 kg/m^3. In the case of steel fibers, it cannot be unequivocally determined after testing.

Conclusions

Fibrous additives do not cause problems at the dosing stage; however, they significantly change the consistency of the concrete. In particular, in the case of the tested polypropylene fibers (P1 and P2) where the consistency class changed from S4 (control concrete) to S1/S2 (series P2-S4). Moreover, with the addition of polypropylene fibers, the workability of the concrete mix changes, resulting in the addition of 2 kg/m^3 of polypropylene fibers (P1 and P2) for the assumed method of laying, in which the assumed vibration time for all of the tested series (2×20 seconds) was insufficient. The inferior consistency of the concretes of the P1-S4 and P2-S4 series resulted in the lack of compaction of the concrete mix in the molds, which translated into the deterioration of the bending strength results in relation to the P1-S3 and P2-S3 series by 3.2% and 4.4%, respectively, and a compressive strength of 1.5% and 3.74%, respectively. The problems with the consistency of the concrete mix did not concern the series with the addition of steel fibers.

The highest compressive strength among the concretes with the addition of polypropylene fibers was achieved by the P2-S3 series (1.5 kg/m^3 of P2 type fibers), which was 7.23% higher compared to the concrete of the control series (SK). In the case of the series with steel fibers, the compressive strength increased as the amount of the added fiber was increased, regardless of the type of the fiber added. The optimal results were obtained by the series with the highest amount of fibers (S1-S4 and S2-S4), enhanced by 25.20% and 29.33%, respectively, in relation to SK. Of all of the series, the highest tensile strength of the concrete in the bend test was achieved by the series S2-S4, which was 38.89% compared to SK. When considering the concrete series with the addition of steel fibers, the series with the addition of hooked fibers (S2) achieved slightly improved results, which is related to the geometry of the fiber, and results in improved anchoring in the concrete. In the case of the polypropylene fibers, the optimal result was obtained from the P2-S3 series, which had a strength that was larger by 16.98% compared to the concrete of the control series.

References

1. Bentur, A. & Mindess, S. (2019) *Fibre Reinforced Cementitious Composites*. London: CRC Press.
2. Do, T.M.D. & Lam, T.Q.K. (2021) Design parameters of steel fiber concrete beams. *Magazine of Civil Engineering* 102(2), pp. 10207–10207, doi: 10.34910/MCE.102.7.
3. Glinicki, M. (2010) *Beton ze zbrojeniem strukturalnym*. In: XXV Ogólnopolskie Warsztaty Pracy Projektanta Konstrukcji, Szczyrk, 10–13 Marca 2010, Tom I, pp. 279–308, Gliwice: PZITB.
4. Helbrych, P. (2021) Effect of dosing with propylene fibers on the mechanical properties of concretes. *Construction of Optimized Energy Potential* 2, pp. 39–44. doi: 10.17512/bozpe.2021.2.05.
5. Ingaldi, M. (2015) Sustainability as an element of environmental management in companies. *Production Engineering Archives* 7/2, pp. 29–32.
6. Jamroży, Z. (2020) *Beton i jego technologie*. Warszawa: Wydawnictwo Naukowe PWN.
7. Jura, J. & Ulewicz, M. (2021) Assessment of the possibility of using fly ash from biomass combustion for concrete. *Materials* 14(21), p. 6708, doi: 10.3390/ma14216708.
8. Kim, J. (2022) Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concretes: An overview. *Construction and Building Materials* 328, p. 127071, doi:10.1016/j.conbuildmat.2022.127071.
9. Kim, J., Grabiec, A.M. & Ubysz, A. (2022) An experimental study on structural concrete containing recycled aggregates and powder from construction and demolition waste. *Materials* 15(7), p. 2458, doi: 10.3390/ma15072458.
10. Kim, J. & Jang, H. (2022) Closed-loop recycling of C&D waste: Mechanical properties of concrete with the repeatedly recycled C&D powder as partial cement replacement. *Journal of Cleaner Production* 343, p. 130977, doi: 10.1016/j.jclepro.2022.130977.
11. Latifi, M.R., Biricik, Ö. & Mardani Aghabaglou, A. (2022) Effect of the addition of polypropylene fiber on concrete properties. *Journal of Adhesion Science and Technology* 36(4), pp. 345–369, doi: 10.1080/01694243.2021.1922221.
12. Ma, M., Tam, V.W., Le, K.N. & Osei-Kuei, R. (2022) Factors affecting the price of recycled concrete: A critical review. *Journal of Building Engineering* 46, p. 103743, doi: 10.1016/j.jobe.2021.103743.
13. Makul, N. (2021) Principles of Fiber-Reinforced Concrete. In Makul, N. (ed.) *Principles of Cement and Concrete Composites*. Cham: Springer International Publishing (Structural Integrity), pp. 79–98, doi: 10.1007/978-3-030-69602-3_4.
14. Pietrzak, A. (2018a) Ocena wpływu recyklatów z butelek pet na wybrane właściwości betonu. *Construction of Optimized Energy Potential* 2018(1), pp. 51–56.
15. Pietrzak, A. (2018b) Wykorzystanie ubocznych produktów współspalania węgla i biomasy w budownictwie jako proekologiczne działanie człowieka. *Construction of Optimized Energy Potential* 2015(1), pp. 159–164.

16. Pietrzak, A. (2019) Wpływ popiołów powstałych ze spalania osadów ściekowych na podstawowe właściwości mechaniczne betonu. *Construction of Optimized Energy Potential* 2019(1), pp. 29–35, doi: 10.17512/bozpe.2019.1.03.
17. Pikus, G.A. (2016) Steel fiber concrete mixture workability. *Procedia Engineering* 150, pp. 2119–2123, doi: 10.1016/j.proeng.2016.07.250.
18. PN-EN 12350-2:2019-07. Badania mieszanki betonowej – Część 2: Badanie konsystencji metodą opadu stożka (no date).
19. PN-EN 12390-1:2021-12. Badania betonu – Część 1: Kształt, wymiary i inne wymagania dotyczące próbek do badań i form.
20. PN-EN 12390-2:2019-07. Badania betonu – Część 2: Wykonywanie i pielęgnacja próbek do badań wytrzymałościowych.
21. PN-EN 12390-3:2019-07. Badania betonu – Część 3: Wytrzymałość na ściskanie próbek do badań.
22. PN-EN 12390-4:2020-03. Badania betonu – Część 4: Wytrzymałość na ściskanie - Wymagania dla maszyn wytrzymałościowych.
23. PN-EN 12390-5. Badania betonu – Część 5: Wytrzymałość na zginanie próbek do badań.
24. PN-EN 14889-1:2007. *Włókna do betonu* – Część 1: Włókna stalowe – Definicje, wymagania i zgodność.
25. PN-EN 14889-2:2007. *Włókna do betonu* – Część 2: Włókna polimerowe – Definicje, wymagania i zgodność.
26. Pribulová, A., Futáš, P. & Baricová, D. (2016) Processing and utilization of metallurgical slags. *Production Engineering Archives* 11/2, pp. 2–5.
27. Purcell, A., Forde, M.M., Maharaj, R. & Maharaj, C. (2021) Optimising the performance of crumb rubber modified concrete. *Journal of Solid Waste Technology and Management* 47(1), pp. 137–145, doi: 10.5276/JSWTM/2021.137.
28. Sharma, N., Sharma, P. & Parashar, A.K. (2022) Use of waste glass and demolished brick as coarse aggregate in production of sustainable concrete. Materials Today: Proceedings [Preprint], doi: 10.1016/j.matpr.2022.04.602.
29. Solahuddin, B.A. & Yahaya, F.M. (2022) Properties of concrete containing shredded waste paper as an additive. Materials Today: Proceedings, 51, pp. 1350–1354, doi: 10.1016/j.matpr.2021.11.390.
30. Tomov, M. & Velkoska, C. (2022) Contribution of the quality costs to sustainable development. *Production Engineering Archives* 28(2), pp. 164–171, doi: 10.30657/pea.2022.28.19.
31. Ulewicz. M. & Pietrzak, A. (2021) Properties and structure of concretes doped with production waste of thermoplastic elastomers from the production of car floor mats. *Materials* 14(4), 872, doi: 10.3390/ma14040872.
32. Zhang, Y., Mao, Y., Jiao, L., Shuai, C. & Zhang, H. (2021) Eco-efficiency, eco-technology innovation and eco-well-being performance to improve global sustainable development. *Environmental Impact Assessment Review* 89, 106580, doi: 10.1016/j.eiar.2021.106580.

Cite as: Helbrych, P. (2022) Mechanical properties of concretes modified with steel fibers and polypropylene. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 71 (143), 56–63.