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Influence of compressive strength and curing time of fiber reinforced concrete on its residual flexural tensile strength

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ABSTRACT

Compressive strength is the basic parameter determining the quality of concrete. The addition of fibers to concrete allows us to create a composite with unique properties. The resulting fiber concrete can be tested in many ways, and one of the most interesting and still developing parameter is the residual flexural tensile strength. The current market situation in the construction industry in Central and Western Europe related to the problem of obtaining qualified manual workers and the prices of building materials encourage the design and thorough testing of increasingly complex products, including modern concrete. The relationship between compressive strength and residual strength is an unexplored area that is worth developing in scientific studies. The article presents the relationship between the compressive strength of designed fibre reinforced concrete and its residual flexural tensile strength. The test program included the analysis of concrete in compressive strength classes: C16/20, C25/30, C30/37 and C70/85 made of cement CEM II/B-V 42.5 R - HSR/NA and CEM I 42.5 N - MSR/NA. In each of the designed concrete classes, two types of hook-shaped steel fibres with variable slenderness (*l*/*d* ratio) of 50 and 67 were used. Fibre dosage was also diversified and set at 20, 30, 40 and 45 kg/m^3 of the concrete mixture. Residual strength tests were performed in accordance with PN-EN 14651 using the ARAMIS device for digital image correlation. The experimental findings showing the relationship between the compressive strength of concrete and its residual flexural tensile strength are included. The experimental data obtained show that increasing the compressive strength class of concrete does not result in an evident increase in the residual flexural tensile strength. The research also analyzed the influence of curing time of concrete on its residual strength, including tests after 28, 180 and 360 days after concreting. The obtained results confirm the significant influence of steel fibres in transferring bending loads. The influence of sample maturation time on the compressive strength of the designed fibre concrete was also confirmed.

Keywords: fibre concrete, residual strength, tensile strength, steel fibre, digital image correlation

INTRODUCTION

Concrete, as the most commonly used building material, is described in detail in many research publications, see [1, 2]. Over the years, the composition of concrete formula and its properties have undergone many modifications and modernizations [3]. Compressive strength is the basic parameter determining the type of concrete. According to [4], we can distinguish classes of compressive strength for ordinary and heavy concrete and classes of compressive strength for lightweight concrete as well. The selection of the concrete compressive strength class depends on the type of the designed structure, its intended use and the assumed service life in the given exploitation conditions. The most commonly designed classes of concrete range from C16/20 to C35/45. The compressive strength of concrete depends on many factors. The water-cement ratio is the crucial one: the lower water-cement ratio (*w*/*c*), the higher compressive strength of concrete [1, 2]. It is worth mentioning that as the *w*/*c* is lowered, the concrete mix becomes less workable, so it is required to use appropriate chemical admixtures [3, 5]. The compressive strength of concrete is also correlated with the type of cement. Depending on the strength class of the cement, the type and amount of the additive, it is possible to obtain concrete with the assumed strength and specific durability parameters, which leads into the quality and service life of the reinforced concrete structures. It is worth mentioning the type of aggregate, which is also important. Depending on the intended use, the type of aggregate plays an important role, e.g. in the case of surface concrete or road and bridge concrete, allowing to achieve the assumed class of concrete and appropriate frost resistance. Mentioning the durability parameters, the air content cannot be omitted. The upper limits of air content (6.5-8.0%) can, on the one hand, lead to improved frost resistance, water penetration under pressure and water absorption, on the other hand – results in the reduction of compressive strength of concrete. Detailed guidelines regarding specific parameters and composition of the concrete mix, depending on the impact of external conditions, are included in exposure classes [4].

Considering strength parameters of concrete in any context, it is obligatory to introduce time as an input parameter. In fact, the final result of the research or analysis and the resulting conclusions or recommendations depend on time [1, 6]. When considering the issue of time for concrete, from the moment of its creation, we can talk about different times: time of mixing substrates, time of workability, time of setting, time of hardening, time of demolding elements, time of drying, time of determining the compressive strength or time of achieving the required durability parameters. Each type of concrete, depending on the selection of ingredients, is characterized by variability of parameters over time. The leading role is played by the amount and type of cement used for the production of the concrete mix. The use of cement from the CEM I group with a strength class of 42.5 or 52.5 [7] and a rapid increase in strength (R) allows us for much faster achievement of compressive strength and durability parameters, which directly leads into the speed of implementation of a given investment [1, 2]. Using cements from the CEM II, CEM III or CEM IV group, we achieve significantly different results depending on the amount and type of cement additive. One of the main additives in the production of both cement and concrete is silica fly ash. It exhibits pozzolanic properties, thanks to which it undergoes a process similar to cement hydration when in contact with water and calcium hydroxide [1, 2, 3]. Granulated blast furnace slag is also a popular addition. Both silica fly ash and blast furnace slag have different properties, but they have a clear impact on the strength and durability of concrete over time, which significantly affects the test results. This dependence was noticed and normalized as a time equivalent to allow us to carry out tests depending on the type of cement used [8].

The compressive strength of concrete and the assumed curing time of the concrete mix can be crucial in the context of designing reinforced concrete structures using steel fibre reinforced concrete. Fibres have been used as an additive to concrete for decades [9]. They fulfill various functions such as reducing shrinkage, limiting the formation of micro cracks, increasing impact resistance or increasing bending strength. The addition of different types of fibres to concrete has been the basis for many studies and research [10–33]. We distinguish fibres for concrete made of many materials. The most commonly used are steel fibres, made of steel of various strength, with variable cross-section and shape. There are also fibres made of various types of plastics (polypropylene, polymer, copolymer), basalt, glass and carbon [9, 14]. One of the main structural members where fibre reinforced concrete is used are industrial floors [15]. The floor slab made of concrete with the addition of fibres (usually steel) has been proven for years as a layer transferring the loads from racks or forklifts. The situation becomes more complicated when fibres would be used as the main reinforcement of other structural members as slabs, beams or columns. It is necessary to meet many technological and execution conditions including homogeneity and randomness of fibre distribution in concrete [15–19]. According to [20] designers are modelling the required reinforcement as the traditional steel bars. The reduction of traditional reinforcing steel bars in favour of fibres added to the concrete mix in the modelling of concrete bending elements is a bold attempt that deserves experimental testing. There is a significant lack of description of this issue in the literature, research and harmonized standard studies. It is true that there are studies on modeling of structural fibre reinforced concrete [21, 22] on a global scale, but this applies only to national studies of few countries. The use of additional load capacity resulting from the provided fibre reinforcement is the issue which requires a lot of detailed investigations [19, 23, 24]. The solutions available on the market, distributed by leading concrete producers, make it possible to use fiber concrete as a structural material in elements such as foundation slabs in detached houses. The article presents the results of experimental tests determining the measured impact of the dosage of different types of fibers on the residual strength, which significantly increases the level of knowledge about fiber concrete and translates into specific application in construction practice.

The residual flexural tensile strength of fibre reinforced concrete is one of the major unknowns in design process which, together with the equivalent flexural strength, is the starting point in the design of fibre concrete structures [18, 25–28]. In this paper the influence of the compressive strength of concrete and the curing time of its samples on its residual flexural tensile strength was analyzed. Two different kinds of fibres with different fibre dosages and four classes of concrete were investigated. The research used the ARAMIS GOM non-contact measurement system. An innovative approach to tests using such a device allowed us for the development of the research method contained in [31], which leads to a significant optimization of the speed and labour consumption in conducting residual strength tests.

LABORATORY TESTS

Two types of hooked steel fibre were used in the tests, according to Table 1. In the first stage the relationship between the compressive strength of concrete and the residual tensile strength was investigated. The fibre dosage was set at 20, 30 and 45 kg/m^3 in each of three classes of concrete: C16/20, C30/37 and C70/85. Fiber dosing is consistent with current construction practice, and the amount of 45 kg/m^3 is currently almost the maximum we can achieve in continuous production of ready-mix concrete. The strength classes were selected based on the most common ones in the design practice of reinforced structures, with the exception of class C70/85, which is a reference to extreme values. The detailed composition of the recipes is presented in Table 2.

For the production of the first three mixes, gravel aggregate and CEM II/B-V 42.5 R - HSR/NA cement were used, whereas in the fourth one basalt aggregate and CEM I 42.5 N MSR/NA cement were used to achieve the assumed compressive strength class. A detailed description and designation of individual mixtures are presented in Table 3. In the second stage, the influence of the curing time of the concrete samples on its residual strength was examined. It was assumed that the beams are tested after the 28, 180 and 360 days from their concreting. This range results from the use of CEM II/B-V cement and fly ash as an addition to the concrete mix. Additionally, time reflects the conditions on the construction site, where horizontal concrete elements made of fiber concrete are often subjected to loads several months after their casting.

For the first 28 days, the samples were stored in conditions compliant with [29], and then in laboratory conditions. A concrete mix of class C25/30 and C30/37 was used for the tests. In

Table 1. Parameters of the fibres used in the research

Symbol	X	Y
Length (*l*) [mm]	50	60
Diameter (*d*) [mm]	1	0,9
Slenderness (*l*/*d*)	50	67
Photo		

Table 2. Composition of concrete recipes

Strength class	C16/20	C25/30	C30/37	C70/85
Aggregate 0/2 [kg/m^3]	852	806	762	597
Aggregate 2/8 [kg/m^3]	398	393	406	567
Aggregate 8/16 [kg/m^3]	541	572	582	749
CEM I 42,5 N - MSR/NA [kg/m^3]	-	-	-	500
CEM II/B-V42,5 R - HSR/NA [kg/m^3]	200	260	300	-
Silica fly ash [kg/m^3]	90	60	40	-
Admixture 1 [kg/m^3]	0,84	1,3	1,3	-
Admixture 2 [kg/m^3]	0,95	1,3	1,65	-
Admixture 3 [kg/m^3]	-	-		5,8
Consistency class	S4	S4	S4	S4

Table 3. Symbol of fibre concrete - study of the relationship between compressive strength and residual strength

Symbol	Strength class	Fibre type	Fibre dosing [kg/m^3]
C20X20	C16/20	X	20
C20X30			30
C20X45			45
C20Y20		Y	20
C20Y30			30
C20Y45			45
C37X20	C30/37	X	20
C37X30			30
C37X45			45
C37Y20		Y	20
C37Y30			30
C37Y45			45
C85X20	C70/85	X	20
C85X30			30
C85X45			45
C85Y20		Y	20
C85Y30			30
C85Y45			45

Table 4. Symbol of fibre concrete - study of the influence of curing time on the residual strength

Symbol	Strength class	Fibre type	Fibre dosing [kg/m^3]	Curing time [days]
C30X40-28	C25/30	X	40	28
C30X40-180				180
C30X40-360				360
C37X40-28	C30/37			28
C37X40-180				180
C37X40-360				360
C30Y20-28	C25/30	Y	20	28
C30Y20-180				180
C30Y20-360				360
C37Y20-28	C30/37			28
C37Y20-180				180
C37Y20-360				360

each of the classes, two types of fibres (X, Y) were used in the dosing of 20 kg/m^3 for Y fibres and 40 kg/m^3 for X fibres. The detailed composition of concrete recipes is presented in Table 2. A detailed description and marking of individual mixes are given in Table 4.

The production of all tested samples took place in the conditions of a concrete production plant in order to reflect reality as much as possible and make the results of the experiments more realistic. The tests were carried out in the Laboratory of the Institute of Building Structures of the Poznan University of Technology in accordance with [31]. A total of 360 beams with dimensions of 150×150×600 mm were made. The test scheme is shown in Figure 1. The spacing of supports was 500 mm (its effective span). The three-point displacement-controlled bending test was conducted at a rate of 0.2 mm/min. In each of the beams, a cut was made in accordance with the standard assumptions.

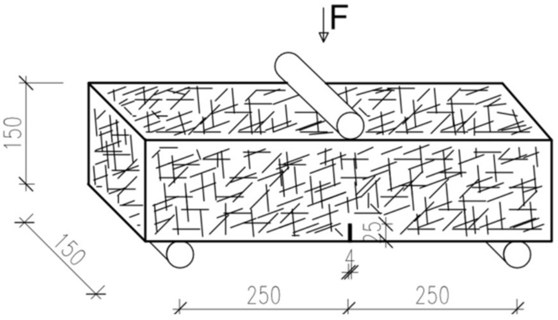

Figure 1. Scheme of the tested beams in accordance with PN-EN 14651

The modern ARAMIS measurement system was used in the laboratory tests, which uses a non-contact measurement method based on the principle of digital image correlation. Figure 2 shows the location of the facet points in the ARAMIS measurement area. The principle of non-contact measurement of the change in the distance between points No. 1 and No. 2 was adopted. These points were located at a distance of about 3 mm from the lower edge of the beam at a distance of about 10 mm between them. In addition, a second pair of facet points (No. 3 and No. 4) was placed, whose mutual change of position was also controlled. The observation of the vertical displacement of point No. 5 made it possible to verify the correctness of the measurement during the test. All distances between the facet points and the edges were measured before the test using an electronic caliper and the ARAMIS system. The image from the tests during the measurement was recorded with a frequency of 5 Hz, which meets the recommendations of the PN-EN 14651 standard. The residual bending tensile strength was determined (according to PN-EN 14651) from the relationship:

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2} \tag{1}$$

where: $f_{R,j}$ – successive residual strength (j = 1,2,3,4), F_j – force corresponding to the achievement of CMODj (according to Fig. 3), l – effective span of the sample, b – sample width, h_{sp} – height of the sample in the cross-section through the crack.

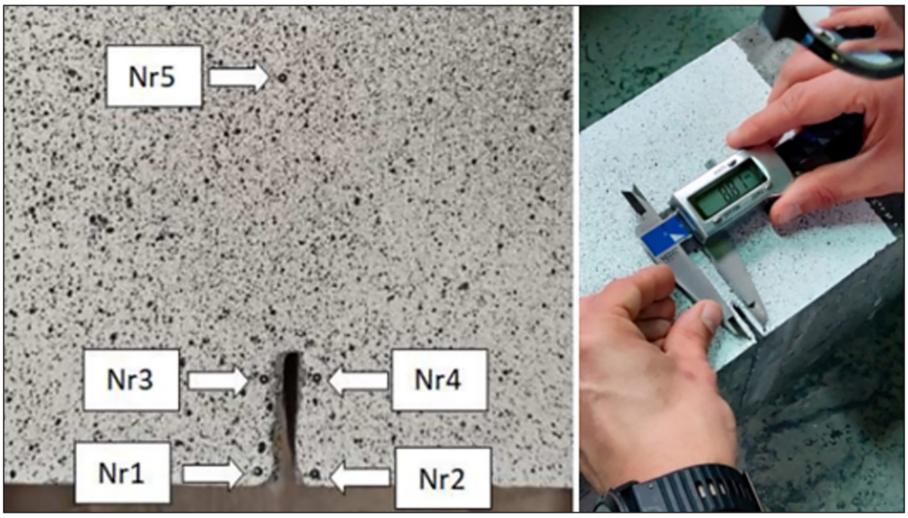

Figure 2. On the left: ARAMIS examination area with marked points of facets (No. 1-No. 5), on the right: measuring the distance between the facets using an electronic caliper

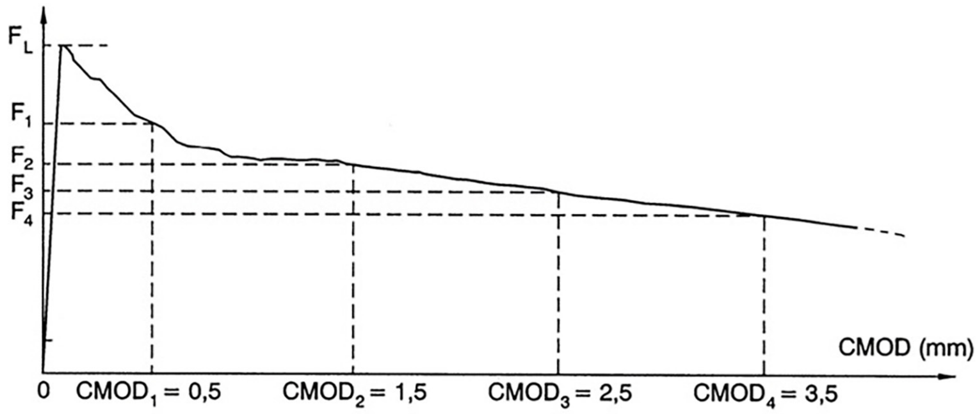

Figure 3. Typical force-CMOD relationship (source: PN-EN 14651)

The results obtained from the ARAMIS measurement were appropriately interpolated so that the CMOD value corresponded to the lower edge of the beam. The effectiveness and correct operation of the ARAMIS system was confirmed by correlation with an electronic extensometer on a sample of 48 beams made of 4 different types of fibre concrete (Fig. 4). Additionally, 180 cubic samples with dimensions of 150×150×150 mm were made to determine the compressive strength in accordance with [30].

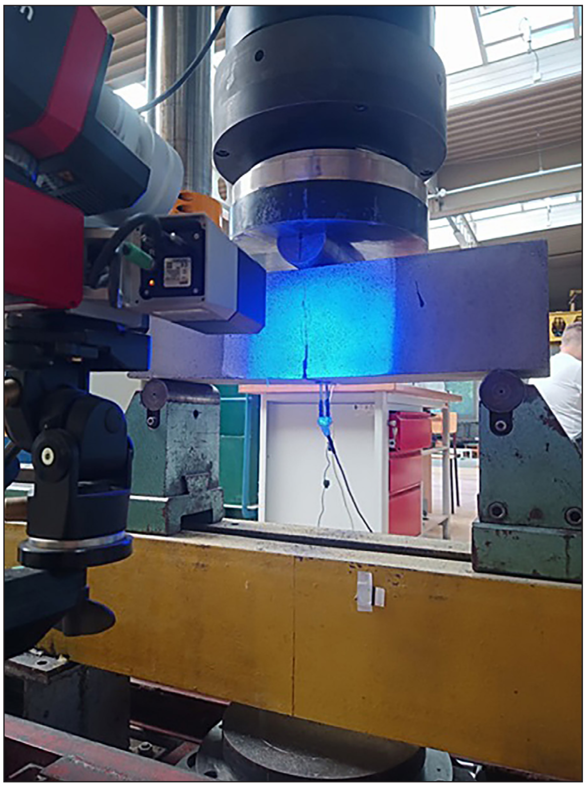

Figure 4. Residual bending tensile strength test in accordance with PN-EN 14651 – correlation of the ARAMIS system with the extensometer

RESULTS

Compressive strength test

The first stage of the research concerned the influence of compressive strength of concrete on its residual flexural tensile strength. The compressive strength was determined based on the average of six samples for each variant of tested concrete mix. Cubic samples with dimensions of 150×150×150 mm were made in concrete factory conditions during the formation of beams for residual strength tests. The consistency of the concrete when making the samples was in the S4 class [4] (Abrams cone slump results from 160–190 mm). Consistency class S4 was chosen because the addition of fibers to concrete causes deterioration of workability and due to the conditions prevailing on building sites in order to avoid deterioration of compressive strength, e.g. by prohibited liquefaction of the mixture with water. At this stage, 108 cubic samples were tested, the results are presented in Table 5.

The mean strength in accordance with [4] for initial production is calculated according to the formula:

$$f_{cm} \geq (f_{ck} + 4)\ \mathrm{N/mm^2} \tag{2}$$

where: f_{cm} – mean compressive strength of concrete; f_{ck} – characteristic compressive strength of concrete.

The results confirm that the compressive strength class has been achieved for each of the designed fibre concretes. The obtained results for concrete class C16/20 are from 31.250 to 39.911 MPa, for class C30/37 from 42.248 to 50.864 MPa, and for class C70/85 from 95.511 to 113.010 MPa. It is worth paying attention to the increase

Table 5. Compressive strength results – 1st stage of testing

Label	Designed strength class of concrete	Compressive strength [MPa]
C20X20	C16/20	31,250
C20X30		34,005
C20X45		39,911
C20Y20		33,766
C20Y30		35,706
C20Y45		37,986
C37X20	C30/37	42,248
C37X30		45,116
C37X45		49,929
C37Y20		44,288
C37Y30		46,563
C37Y45		50,864
C85X20	C70/85	95,511
C85X30		97,929
C85X45		106,837
C85Y20		105,126
C85Y30		113,010
C85Y45		109,901

in compressive strength that was observed as the fibre content in the concrete mixture increased. This increase was observed when both types of fibres were used, but its amount does not affect the further course of the research. Only in one case was the compressive strength of concrete with a fibre amount of 30 kg/m^3 (C85Y30) higher than that of concrete with a fibre amount of 45 kg/m^3 (C85Y45). This situation may be caused by the level of homogenization and the composition of the concrete mixture itself that, when using a strong polymer, had a high viscosity reaching above 100 MPa. Additionally, the use of fibers with a slenderness above 0.6 makes it difficult to uniformly distribute this additive in the concrete mix, which may be reflected in the compressive strength results when crushed basalt aggregate is used. In the next part of the research, the compressive strength was analyzed in relation to the test time. The initial strength of 28 days was assumed, and the two subsequent test dates were set at 180 days and 360 days from the moment of producing the concrete mixture. The compressive strength results presented in Table 6 are the average of 6

Table 6. Compressive strength results – 2nd stage of testing

Label	Designed strength class of concrete	Curing time [days]	Compressive strength [MPa]
C30X40-28	C25/30	28	34,975
C30X40-180		180	38,083
C30X40-360		360	41,650
C37X40-28	C30/37	28	44,599
C37X40-180		180	51,695
C37X40-360		360	56,399
C30Y20-28	C25/30	28	38,201
C30Y20-180		180	44,902
C30Y20-360		360	46,287
C37Y20-28	C30/37	28	46,678
C37Y20-180		180	51,598
C37Y20-360		360	59,854

samples for each type of fibre concrete (a total of 72 cubic samples were tested at this stage).

The obtained results confirm that the compressive strength class was achieved as intended. Four types of fibre concrete were tested, and in each type the compressive strength increased over time. For class C25/30 the increase of strength in comparison with 28-days strength after 180 and 360 days was 19 and 21%, respectively, and for class C30/37 was 26 and 28%. The increase in concrete strength over time is a natural phenomenon, especially for mixtures containing silica fly ash, which has pozzolanic properties. The tested concretes were produced using CEM II/B-V 42.5 R-HSR/NA cement, which contains up to 35% of the addition of silica fly ash in accordance with [2]. Additionally, the recipe used fly ash as an additive in amounts of 60 and 40 kg, which also resulted in an increase in compressive strength results over time.

Residual flexural tensile strength test

Residual strength tests were carried out in accordance with PN-EN 14651. In the first stage, the influence of concrete's compressive strength on its residual strength was examined. Concrete classes C16/20, C30/37 and C70/85 were selected. The mixtures used two types of fibres in three different dosages (20, 30 and 45 kg). Twelve test beams with dimensions of 150×150×600 mm were made of each type of fibre concrete (a total of 216 beams in the first stage). The results converted into MPa for individual types of fibre concrete are presented in the charts below (Figs. 5–8).

The residual strength results for concrete class C16/20 depend on the type and amount of steel fibre used (Fig. 5). Concrete using Y fibre is characterized by higher residual strength, which is due to the greater slenderness of the fibre used.

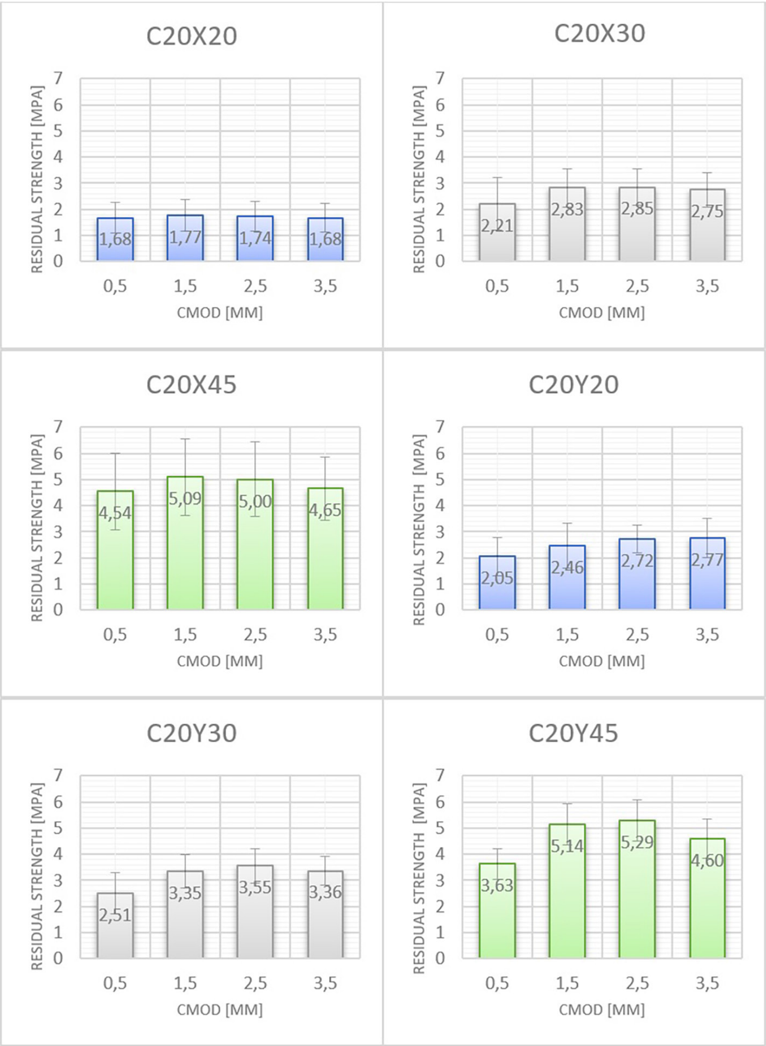

Figure 5. Residual flexural strength (in MPa) vs. CMOD (in mm) for concrete class C16/20 with two kinds of steel fibres (X, Y) and fibre dosage in the amount of 20, 30 and 45 kg/m^3

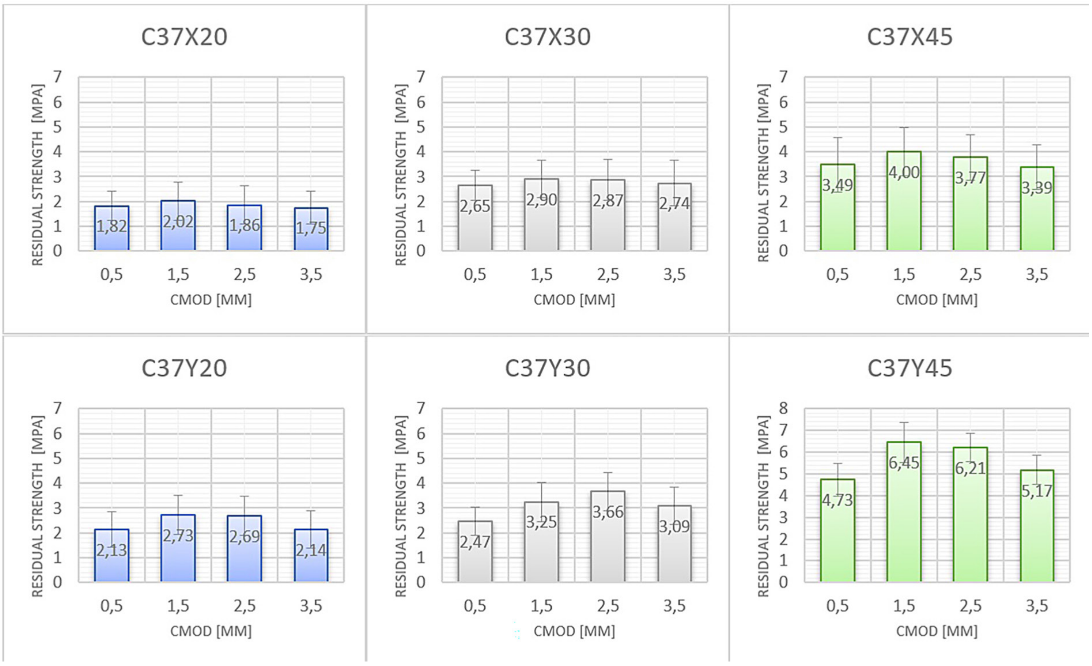

Figure 6. Residual flexural strength (in MPa) vs. CMOD (in mm) for concrete class C30/37 with two kinds of steel fibres (X, Y) and fibre dosage in the amount of 20, 30 and 45 kg/m^3

In both cases, the used fibre types lead to an increase of compressive strength as the fibre dosage increases. For CMOD 2.5 and X fibres, the residual strength is 1,74 MPa for a dosage of 20 kg/m^3, then with a fibre dosage of 30 kg/m^3 it increases to 2,85 MPa, and at 45 kg/m^3 it increases to 5,00 MPa.

The graphs in Figure 6 show the results of residual strengths for concrete class C30/37. Similarly to the results for C16/20 concrete, as the fibre dosage increases, its residual bending tensile strength increases. For CMOD 2.5, when X-fibres were dosed in an amount of 20 kg/m^3, a value of 1.86 MPa was achieved, with a dosage

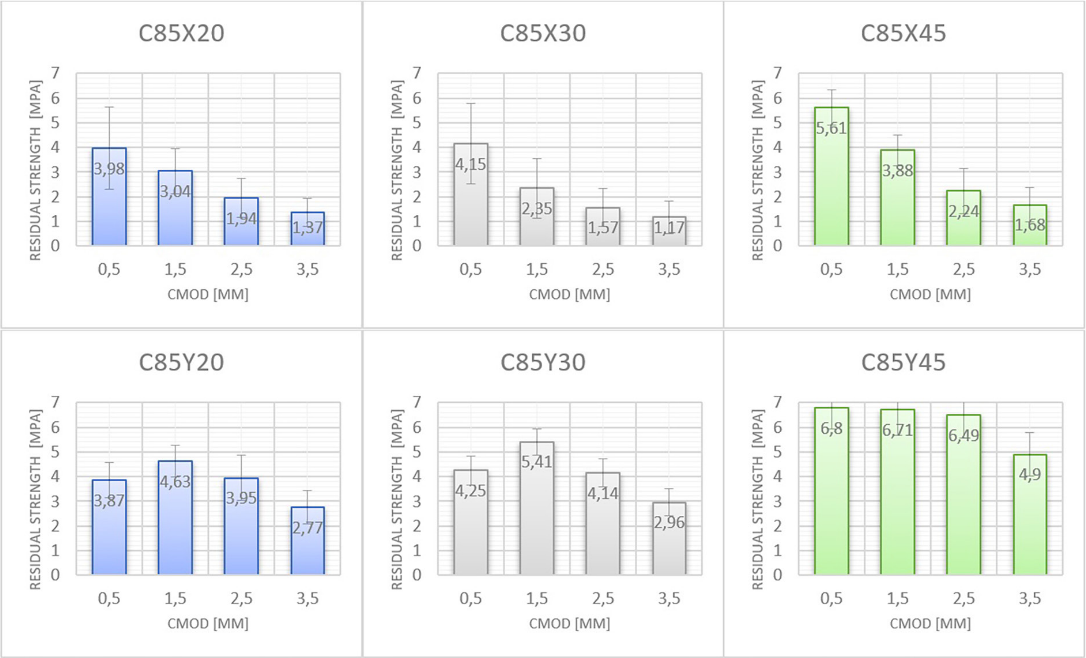

Figure 7. Residual flexural strength (in MPa) vs. CMOD (in mm) for concrete class C70/85 with two kinds of steel fibres (X, Y) and fibre dosage in the amount of 20, 30 and 45 kg/m^3

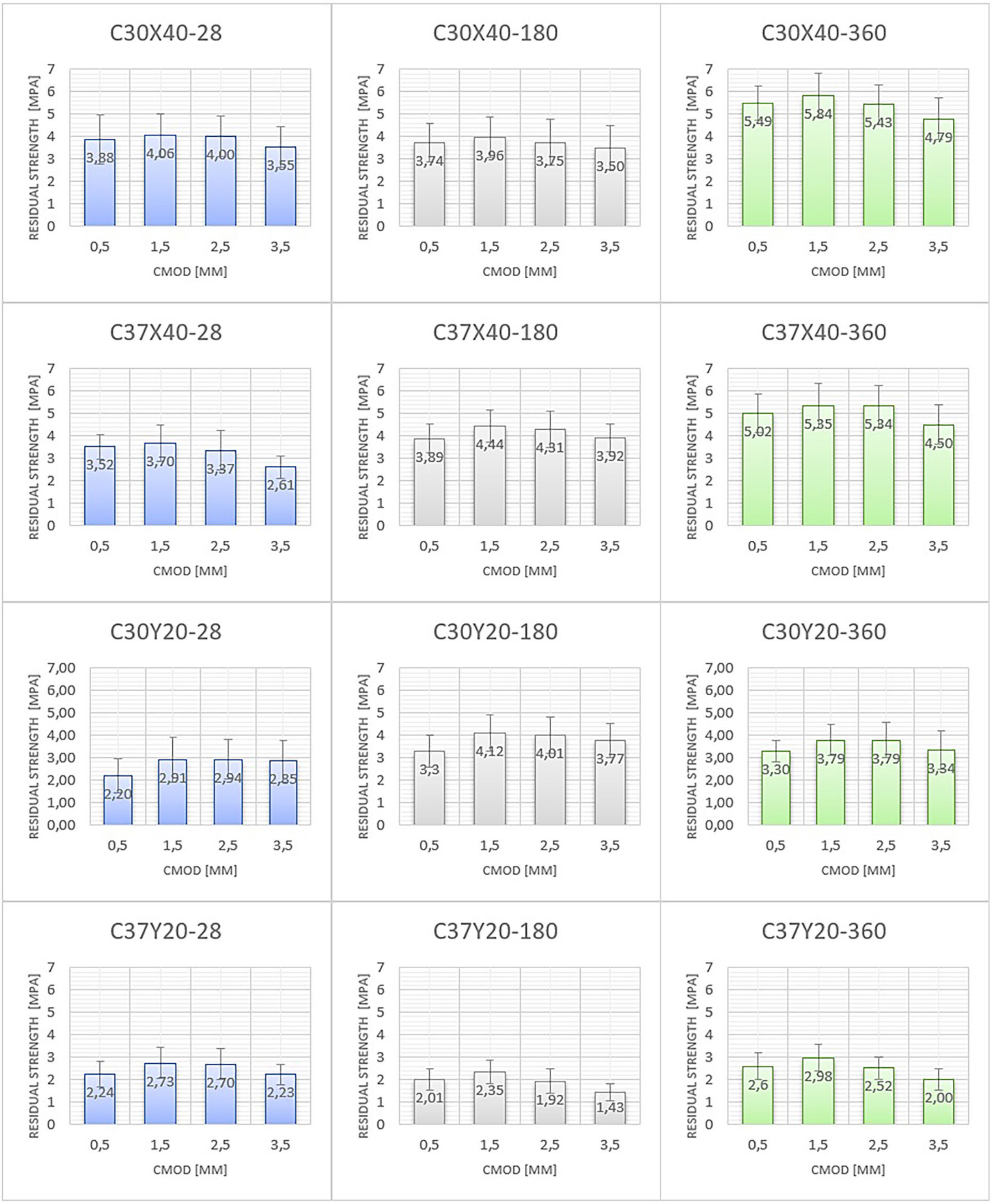

Figure 8. Residual flexural strength (in MPa) vs. CMOD (in mm) for concrete classes C25/30 and C30/37 determined after the 28, 180 and 360 days of curing

of 30 kg/m^3 the value increased to 2.87 MPa, then with a dosage of 45 kg/m^3 a level of 3.77 MPa was recorded. When comparing the residual strength charts for concrete classes C16/20 and C30/37, no significant differences are observed, the compressive strength class of concrete does not generate an increase in residual strength. For CMOD 2.5, with the dosage of X-fibre in the amount of 45 kg/m^3 in concrete class C30/37 (C37X45), a decrease in residual strength was observed to 3.77 MPa compared to class C16/20 (C20X45) 5.00 MPa, with a difference in strength compressive strength of approximately 10 MPa. In turn, with the same amount of Y fibres, the opposite results were recorded, i.e. an increase in residual strength from 5.29 MPa to 6.21 MPa, with a difference in compressive strength of approximately 13 MPa. These differences are not large enough to constitute a significant impact of compressive strength on residual strength, but rather indicate the influence of factors such as random fibre distribution.

The results presented in Figure 7 concern the residual strengths for C70/85 class concrete. This concrete achieved a compressive strength above 100 MPa, which resulted in significant differences in the MPa-CMOD relationship charts. Such a high class of concrete was deliberately introduced into the research plan in order to verify the influence of concrete's compressive strength on its residual strength. Also, an increased amount of fibres was intentionally used, up to 45 kg/m^3, to demonstrate the relationship between the residual strength and the amount of fibres in the concrete mix. Analyzing the graphs in Figure 7 for X fibres, a significant increase in residual strength was found for CMOD 0.5, which was influenced by the compressive strength of concrete. However, for CMOD 2.5 and 3.5 the situation is opposite, and residual strength decreases of over 100% were observed. The reason for this situation may be the brittleness of concrete with a strength above 100 MPa. For Y fibres at CMOD 0.5 the results are the same, an increase in residual strength is observed, while for CMOD 2.5 and 3.5 the results do not differ from the concrete classes C16/20 and C30/37. This proves the significant impact of the type and amount of fibre used on the residual strength.

In the second stage of the research, the influence of curing time on the residual strength was checked. For this purpose, 144 beams were made (12 pieces of each type of fibre concrete), which were tested for residual tensile strength in bending after 28, 180 and 360 days after forming. The results in the form of graphs are presented in Figure 8. For X fibres in class C25/30, no significant differences were observed between the 28th and 180th day of the test, but after 360 days the residual strength increased by approximately 1.5 MPa. For X-fibres in the C30/37 class, an increase of approximately 1 MPa was observed between the 28th and 180th day of sample curing time, and an increase between the 180th and 360th day of testing also by approximately 1 MPa. In mixtures using Y fibres, no such significant differences are observed. It is true that in the case of C30Y20-180 concrete, the results increased by more than 1 MPa compared to C30Y20-28, but the remaining results are characterized by greater stability than in the case of X fibres. For the C30/37 concrete class, when dosing Y fibres, a decrease in strength was observed in the test after 180 days of ripening (CMOD 2.5 and 3.5). When using X fibres, an increase in residual strength over time was observed, but for Y fibres the residual strength did not change much. The reasons for this situation include the type of fibre used, its slenderness, variable shape or the type of steel from which it was made, which may translate into the interaction of the concrete matrix with the fibre surface.

CONCLUSIONS

Based on the performed laboratory tests of fibre concrete in strength classes C16/20, C25/30, C30/37 and C70/85 with variable dosing of two types of steel fibres, the following conclusions can be formulated:

- residual bending tensile strength depends mainly on the type and amount of fibre used,
- fibres with increased slenderness (>50) allow for higher values of residual tensile strength under bending,
- the use of steel fibres in the concrete mix increases the compressive strength of concrete,
- the curing time of the samples affects positively the compressive strength of concrete, especially when the mixture is produced with high-quality fly ash,
- the compressive strength of concrete in the range of 30–50 MPa has no influence on the residual strength,
- compressive strength of concrete above 90 MPa improves the residual strength in the initial phase of load transfer, but after cracking occurs, the compressive strength of concrete ceases to be significant, and the required load-bearing capacity can be obtained by using the appropriate type of fibres,
- the obtained results of residual strengths for X and Y fibers in the dosage range of up to 30 kg/m^3 reflect the values shown in the available literature.
- the results of the residual strength for a fiber dosage of 45 kg/m^3 (especially Y) are characterized by its high value even with crack opening for CMOD 2.5
- the concrete curing time has a clear impact on compressive strength, but does not clearly translate into residual bending tensile strength,

- for safety reasons, it is recommended to use a 28-day strength for the design of elements made of fibre concrete,
- the use of fibre concrete with steel fibres and a strength greater than 40 MPa for structural elements is economically disadvantageous, because the results for CMOD 2.5 and CMOD 3.5 (after crack formation) depend on the type and amount of fiber used and not on the strength class of the concrete.
- the applied innovative method of optical measurement of displacements and strains in the residual strength analysis is a useful alternative to the traditional method using an extensometer
- the results of the conducted laboratory tests will be helpful in developing guidelines for the design of structural elements made of fibre-reinforced concrete.

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