Gripping of Anchor Fiber of Ukrainian Production with Fine-Grain Concrete

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Abstract. The results of tests for drawing anchor fibers with a length of 50 mm and a diameter of 1 mm, laid at the end of concrete prisms 50x50x100 mm made of fine-grained concrete of classes C 20/25, C25/30 and C 30/35 are presented. From the tests of 50 fibers, the average value of tensile strength was determined, which is equal to 1242 MPa with a coefficient of variation of 2.1%. Prisms were made of fine-grained concrete, which included cement with an activity of 41.2 MPa for concrete class C 20/25 and an activity of 50.8 MPa for concrete classes C 25/30 and C 30/35. Sand with a modulus of size 2.1 was used as a filler. The concrete mixture was prepared in a forced concrete mixer, and the concrete was compacted on a vibrating platform. Simultaneously with these prisms, cubes with dimensions of 150x150x150 mm and prisms with dimensions of 100x100x400 mm were made to determine the bottom and prism strength of concrete. The length of laying fibers into concrete was 10,15 and 25 mm. It is shown that the forces perceived by the end anchors and the smooth part of the fibers rise with increasing strength of concrete. The results of tests for drawing fibers from concrete prisms are given in tables 1 - 3. For the length of laying fiber 10 mm into prisms with strength $f_{cm,\text{cube}} = 29.31 \text{MPa}$ and $f_{cm,\text{prism}} = 23.15 \text{MPa}$ the maximum stresses during drawing were 515.30 - 549.04 MPa (average value - 532.10 MPa). At the same length of laying fiber into concrete prisms with strength $f_{cm,\text{cube}} = 34.76 \text{MPa}$ and $f_{cm,\text{prism}} = 27.11 \text{MPa}$, these stresses were equal to 554.47 - 588.54 MPa (average value - 569.70 MPa). For the length of laying the fiber 10 mm into prisms with strength $f_{cm,\text{cube}} = 38.96 \text{MPa}$ and $f_{cm,\text{prism}} = 31.14 \text{MPa}$, the maximum tensile stresses were 590.51 - 621.72 MPa (average value - 606.81 MPa). At the specified strengths of the prism concrete, the maximum values of the average stresses for fiber drawing were on average 13.37 MPa for concrete of class C20/25 and an activity of 41.2 MPa for concrete of class C20/25 and an activity of 50.8 MPa for concrete classes C 25/30 and C 30/35. Sand with a modulus of size 2.1 was used as a filler. The concrete mixture was prepared in a forced concrete mixer, and the concrete was compacted on a vibrating platform. Simultaneously with these prisms, cubes with dimensions of 150x150x150 mm and prisms with dimensions of 100x100x400 mm were made to determine the bottom and prism strength of concrete. The length of laying fibers into concrete was 10,15 and 25 mm. It is shown that the forces perceived by the end anchors and the smooth part of the fibers rise with increasing strength of concrete. The results of tests for drawing fibers from concrete prisms are given in tables 1 - 3. For the length of laying fiber 10 mm into prisms with strength $f_{cm,\text{cube}} = 29.31 \text{MPa}$ and $f_{cm,\text{prism}} = 23.15 \text{MPa}$ the maximum stresses during drawing were 515.30 - 549.04 MPa (average value - 532.10 MPa). At the same length of laying fiber into concrete prisms with strength $f_{cm,\text{cube}} = 34.76 \text{MPa}$ and $f_{cm,\text{prism}} = 27.11 \text{MPa}$, these stresses were equal to 554.47 - 588.54 MPa (average value - 569.70 MPa). For the length of laying the fiber 10 mm into prisms with strength $f_{cm,\text{cube}} = 38.96 \text{MPa}$ and $f_{cm,\text{prism}} = 31.14 \text{MPa}$, the maximum tensile stresses were 590.51 - 621.72 MPa (average value - 606.81 MPa). At the specified strengths of the prism concrete, the maximum values of the average stresses for fiber drawing were on average 13.37 MPa for concrete of class C20/25, 14.34 MPa for concrete of class C25/30 and 15.27 MPa for concrete of class C30/35. With a fiber laying length of 15 mm into prisms with concrete strength corresponding to class C20/25, the maximum tensile stresses were 575.80 - 607.64 MPa (average value - 587.10 MPa). With such a length of laying fiber into prisms made of concrete class C25/30, these stresses were equal to 614.44 - 680.25 MPa (average value - 638.95 MPa). At the length of laying the fiber 15 mm into the prisms of concrete class C30/35, the maximum stresses during drawing were 681.14 - 692.99 MPa (average value - 685.44 MPa). The maximum values of average stresses for fiber drawing were on average 9.87 MPa for concrete of class C20/25, 10.70 MPa for concrete of class C25/30 and 11.52 MPa for concrete of class C30/35. At a fiber laying length of 25 mm into prisms with concrete strength corresponding to class C20/25, the maximum tensile stresses were 645.44 - 735.03 MPa (average value - 692.76 MPa). With such a length of laying fiber into prisms made of concrete class C25/30, these stresses were equal to 736.58 - 773.25 MPa (average value - 752.37 MPa). With the length of laying fiber 25 mm into prisms made of concrete class C30/35, maximum stresses during drawing were equal to 780.27 - 839.49 MPa (average value - 809.12 MPa). The maximum values of the average stresses during fiber drawing were on average 6.97 MPa for concrete of class C20/25, 7.57 MPa for concrete of class C25/30 and 8.12 MPa for concrete of class C30/35. The coefficient of anchoring capacity $\eta$, which under Ukrainian standards of fibroconcrete structures designing is equal to 0.9, as shown by

\[ \eta = \frac{f_{\text{cm,\text{base}}}}{f_{\text{cm,\text{prism}}}} \]

where $f_{\text{cm,\text{base}}}$ is the base strength of concrete and $f_{\text{cm,\text{prism}}}$ is the prism strength of concrete.
the data of our experiments, is not constant, so it is necessary to take this into account in the formula for determining the tensile strength of fibroconcrete.

1. Introduction

Tangential stresses during the extraction of fibers from concrete are one of the factors influencing the tensile strength of reinforced concrete [1]. Therefore, experimental and theoretical studies are aimed at developing fibers with such strength, deformation and geometric parameters that would provide optimal values of strength, crack resistance and deformability of reinforced concrete. In the article [2] the substantiation of parameters of steel fibers with optimum properties from the point of view of the form, the size and mechanical characteristics is described. One of the rational types of steel fiber is fiber with curved ends [3], thus, modeling its operation at different angles of inclination to the crack front is important because it affects both the load-bearing capacity of reinforced elements and deformability. The evaluation of the efficiency of steel fiber with curved ends is also facilitated by the comparison of experimental data obtained using other types of fibers [4-6]. The authors of the article [7] point out that the tensions when pulling the anchor fiber were better than tensions when pulling the straight fiber to a length of 10 mm, which indicates the need for additional experimental verification of this fact, as the effectiveness of using fibers with curved ends was found experimentally [8, 9].

By calculating the bearing capacity of bending reinforced concrete elements, the tensile strength of reinforced concrete is determined [10]. It depends on the coefficient η, which takes into account the adhesion of fibers to concrete. The national standard [10] for anchor fiber states that the characteristic value of the tensile strength of fiber \( f_{fk} \) should not be less than 800 MPa, and the coefficient of anchoring capacity η for this fiber is equal to 0.9. It should be noted that the coefficient η is assigned only in the first approximation, and not in the same way as it was done for fiber from the sheet [11], or even earlier for the rod reinforcement [12]. Therefore, a detailed study of the adhesion of fiber to the concrete matrix, testing for pulling fiber from concrete, appropriate processing of experimental data will provide reasonable calculation parameters that are used to determine the load-bearing capacity of elements of reinforced concrete structures.

2. Materials, designs of prototype samples, test program

According to the results of the analysis of experimental-theoretical researches and experience of using the steel-fiber-concrete designs, the following conditions of experiment are accepted:

- strength of fine-grained concrete-matrix of prototypes-prisms in the sizes of 50х50х100 mm is intended such that would correspond to classes on durability on axial compression С20/25, С25/30 and С30/35 to cover the range of forces which are most often accepted in real designs;
- the length of laying fibers in the end face of the prism is 10, 15, 25 mm.

The geometric dimensions of the anchor fiber of Ukrainian production are given in Figure 1. The diameters of the fibers were measured with a micrometer. Preliminarily 50 fibers were tested for tension and the average value of strength (1242 MPa) by the coefficient of variation of strength (2.1%) was determined.

The prototypes were made of fine-grained concrete on sand with a modulus of 2.1 mm and anchor steel fiber type HE 1050 with a length of 50 mm and a diameter of 1 mm. Cement of grade 400 (activity type - 42.3) was used as a binder for the production of fine-grained concrete of class C20/25 and cement of grade 500 (activity type - 50.9) for fine-grained concrete of classes C25/30 and C30/35.

![Figure 1. Geometric dimensions of fiber type HE 1050 produced by JSC “Silur”](image-url)
To determine the maximum adhesion forces of the fiber, prisms 50x50x100 mm were made of fine-grained concrete with a strength corresponding to the concrete classes C20/25, C25/30, C30/35, at the end of the prisms dispersed reinforcement at different depths was filled (Figure 2).

Figure 2. Samples of prisms with fiber embedded in their end, after being manufactured

The series differed in the strength of the prisms and the length of laying the fiber into the concrete. The molds were filled with the mixture, which was compacted on a vibrating table, and after 3 hours the concrete surface was covered with a layer of wet sawdust. The samples were stripped after three days, and then stored in a layer of sawdust, which was moistened every two days. Samples were tested after 28 days of storage. Simultaneously with the samples of each series, three cubes of 150x150x150 mm and three prisms of 100x100x400 mm were formed to determine the bottom and prism strength. The strength of the concrete matrix for class C20/25 was equal to: $f_{cm,\text{cube}} = 29.31\,\text{MPa}$ and $f_{cm,\text{prism}} = 23.15\,\text{MPa}$. for class C25/30: $f_{cm,\text{cube}} = 34.76\,\text{MPa}$ and $f_{cm,\text{prism}} = 27.11\,\text{MPa}$. for class C30/35: $f_{cm,\text{cube}} = 38.96\,\text{MPa}$ and $f_{cm,\text{prism}} = 31.14\,\text{MPa}$.

The mixture was prepared in a forced concrete mixer. After the readiness of the concrete, part of the concrete mixture required for the formation of cubes of 150x150x150 mm and prisms of 400x100x100 mm was selected.

Tests of fiber for tension and extraction from the ends of the prisms (Figure 3) were performed on a bursting machine P - 0.5 at a loading speed of 0.05 mm/s.

3. Results and discussions

The test results for drawing fibers from concrete prisms are presented in tables 1 - 3. For the length of laying fiber 10 mm in prisms with strength $f_{cm,\text{cube}} = 29.31\,\text{MPa}$ and $f_{cm,\text{prism}} = 23.15\,\text{MPa}$, the maximum stresses during drawing were 515.30 - 549.04 MPa (average value - 532.10 MPa).

At the same length of laying fiber into concrete prisms with strength $f_{cm,\text{cube}} = 34.76\,\text{MPa}$ and $f_{cm,\text{prism}} = 27.11\,\text{MPa}$ these stresses were equal to 554.47 - 588.54 MPa (average value - 569.70 MPa).
For the length of laying the fiber 10 mm into prisms with strength $f_{cm,cube} = 38.96 MPa$ and $f_{cm,prism} = 31.14 MPa$, the maximum tensile stresses were 590.51 - 621.72 MPa (average value - 606.81 MPa).

![Figure 3. Tests for extracting fiber from concrete prisms 50x50x100 mm](image)

At the specified strengths of the prisms concrete, the maximum values of the average stresses for fiber drawing were on average 13.37 MPa for concrete of class C20/25, 14.34 MPa for concrete of class C25/30 and 15.27 MPa for concrete of class C30/35.

It is known that the average tangential stresses when pulling smooth reinforcement from concrete may have values of 2.0 - 4.5 MPa [12]. When extracting anchor fibers from concrete, they, according to the experiments presented in tables 1 - 3, are several times larger. It means that the end anchors of the fibers provide for the length of the laying of 10 mm perception of a significant part of the load applied to the fiber.

With a fiber laying length of 15 mm into prisms with concrete strength corresponding to class C20/25, the maximum tensile stresses were 575.80 - 607.64 MPa (average value - 587.10 MPa). With such a length of laying fiber into prisms made of concrete class C25/30, these stresses were equal to 614.44 - 680.25 MPa (average value - 638.95 MPa).

At the length of laying the fiber 15 mm into the prisms of concrete class C30/35, the maximum stresses during drawing were 681.14 - 692.99 MPa (average value - 685.44 MPa).

The maximum values of average stresses for fiber drawing were on average 9.87 MPa for concrete of class C20/25, 10.70 MPa for concrete of class C25/30 and 11.52 MPa for concrete of class C30/35.
Table 1. Test results of fibers extraction from the prisms (concrete class C20/25)

| Prism matrix strength $f_{c,prism}$, MPa | Embedment length of the fiber $l_e$, mm | Diameter of the fiber $d_f$, mm | The cross-sectional area of the fiber $A_f$, mm$^2$ | Extraction force $N$, N | Maximum stresses in the fiber during extraction $\sigma_f$, MPa | The maximum average length of the fiber tangential stresses during extraction $\tau_f$, MPa |
|----------------------------------------|----------------------------------------|-------------------------------|----------------------------------------|-----------------|-----------------|-----------------|
| 10                                     | 1                                      | 0.785                         | 431                                   | 549.04          | 13.73           |
| 1.01                                   | 1                                      | 0.785                         | 420                                   | 535.03          | 13.38           |
| 1.02                                   | 1                                      | 0.785                         | 427                                   | 543.95          | 13.60           |
| 1                                      | 1                                      | 0.785                         | 421                                   | 515.30          | 13.14           |
| 1.02                                   | 1                                      | 0.785                         | 415                                   | 528.66          | 13.22           |
| 23.15                                  | 15                                     | 1                             | 0.785                                 | 477             | 607.64          | 10.13           |
| 1.02                                   | 1                                      | 0.817                         | 482                                   | 589.96          | 10.03           |
| 1.01                                   | 1                                      | 0.817                         | 452                                   | 575.80          | 9.60            |
| 1.02                                   | 1                                      | 0.817                         | 472                                   | 577.72          | 9.82            |
| 1                                      | 1                                      | 0.785                         | 459                                   | 584.71          | 9.75            |
| 25                                     | 15                                     | 1                             | 0.801                                 | 563             | 702.87          | 7.10            |
| 1.01                                   | 1                                      | 0.801                         | 553                                   | 704.46          | 7.04            |
| 1.01                                   | 1                                      | 0.801                         | 527                                   | 657.93          | 6.71            |
| 1.01                                   | 1.01                                  | 0.801                         | 517                                   | 645.44          | 6.52            |
| 1                                      | 1                                      | 0.785                         | 558                                   | 710.83          | 7.11            |
| 1                                      | 1                                      | 0.785                         | 577                                   | 735.03          | 7.35            |

At a fiber laying length of 25 mm into prisms with concrete strength corresponding to class C20/25, the maximum tensile stresses were 645.44 - 735.03 MPa (average value - 692.76 MPa). With such a length of laying fiber into prisms made of concrete class C25/30, these stresses were equal to 736.58 - 773.25 MPa (average value - 752.37 MPa).

At the length of laying fiber 25 mm into the prisms of concrete class C30/35, the maximum stress during drawing was equal to 780.27 - 839.49 MPa (average value - 809.12 MPa).

The maximum values of the average stresses during fiber drawing were on average 6.97 MPa for concrete of class C20/25, 7.57 MPa for concrete of class C25/30 and 8.12 MPa for concrete of class C30/35.

In the norms [10] the length of the anchoring of the fiber $l_{fb}$, which ensures its rupture during extraction, is calculated by the formula:

$$l_{fb} \geq \frac{\eta_f d_f f_{fk}}{f_{ck}},$$

where $\eta_f$ is the coefficient that takes into account the anchoring of the fiber, which for the anchor fiber is equal to 0.9;

$f_{fk}$ - characteristic tensile strength of fiber;
$f_{ck}$ is the characteristic value of concrete compressive strength.

### Table 2. Test results of fibers extraction from the prisms (concrete class C25/30)

| Prism matrix strength $f_{c, prism}$, MPa | Embedment length of the fiber $l_e$, mm | Diameter of the fiber $d_f$, mm | The cross-sectional area of the fiber $A_f$, mm$^2$ | Extraction force $N$, N | Maximum stresses in the fiber during extraction $\sigma_f$, MPa | The maximum average length of the fiber tangential stresses during extraction $\tau_f$, MPa |
|------------------------------------------|----------------------------------------|-------------------------------|-----------------------------------|-----------------|-----------------|-----------------|
| 27.11                                    | 10                                     | 1.01                          | 0.801                             | 449             | 560.55          | 14.16           |
|                                          |                                         | 1                             | 0.785                             | 462             | 588.54          | 14.71           |
|                                          |                                         | 1.01                          | 0.801                             | 451             | 563.05          | 14.22           |
|                                          |                                         | 1                             | 0.785                             | 455             | 579.62          | 14.49           |
|                                          |                                         | 1.02                          | 0.817                             | 453             | 554.47          | 14.14           |
|                                          |                                         | 1                             | 0.785                             | 449             | 571.97          | 14.30           |
| 25                                       | 15                                     | 1                             | 0.785                             | 509             | 648.41          | 10.81           |
|                                          |                                         | 1                             | 0.785                             | 499             | 635.67          | 10.59           |
|                                          |                                         | 1.01                          | 0.801                             | 494             | 616.73          | 10.38           |
|                                          |                                         | 1                             | 0.785                             | 534             | 680.25          | 11.34           |
|                                          |                                         | 1.02                          | 0.817                             | 502             | 614.44          | 10.45           |
|                                          |                                         | 1                             | 0.785                             | 501             | 638.22          | 10.64           |

This formula follows from the results of research on the extraction of rod reinforcement from concrete [12]:

$$l_e = \frac{\eta \sigma_S}{f_{c, prism}},$$

where $\Theta$ is the diameter of the rod;

$\sigma_S$ - stress in the reinforcing rod during extraction.

This formula for the case of extracting fiber from concrete can be written as follows:

$$l_e = \frac{\eta \sigma_f}{f_{c, prism}}.$$  

According to the results of our experiments, the values of the coefficients $\eta$ were determined, which depend on the length of laying the fiber into the concrete and the strength of the concrete (table 4).

At the same lengths of fiber laying, this coefficient increases with increasing strength of concrete. Within a particular class of concrete, it increases with increasing length of fiber laying. The reason that this coefficient is not constant, in our opinion, is that this fiber contains anchors, which at short lengths of laying fiber in concrete provide a significant increase in fiber stresses during its extraction. This effect of the anchor on the stress of the fiber during extraction from concrete decreases with increasing length of its laying.
Table 3. Test results of fibers extraction from the prisms (concrete class C30/35)

| Prism matrix strength $f_{c, prism}$, MPa | Embedment length of the fiber $l_e$, mm | Diameter of the fiber $d_f$, mm | The cross-sectional area of the fiber $A_f$, mm² | Extraction force $N$, N | Maximum stresses in the fiber during extraction $\sigma_f$, MPa | The maximum average length of the fiber tangential stresses during extraction $\tau_f$, MPa |
|------------------------------------------|----------------------------------------|-------------------------------|---------------------------------|------------------|----------------------------------|----------------------------------|
|                                          |                                        |                               |                                 |                  |                                  |                                  |
|                                          |                                        |                               |                                 |                  |                                  |                                  |
| 31.14                                   | 1                                      | 0.785                         | 499                             | 610.77           | 15.03                            |                                  |
|                                          | 1.02                                   | 0.817                         | 488                             | 621.72           | 15.70                            |                                  |
|                                          | 1.01                                   | 0.801                         | 488                             | 621.66           | 15.54                            |                                  |
|                                          | 1.01                                   | 0.801                         | 473                             | 590.51           | 14.91                            |                                  |
|                                          | 1.01                                   | 0.801                         | 467                             | 594.90           | 14.87                            |                                  |
| 25                                       | 1                                      | 0.785                         | 538                             | 685.35           | 11.42                            |                                  |
|                                          | 1.02                                   | 0.817                         | 557                             | 681.76           | 11.59                            |                                  |
|                                          | 1.01                                   | 0.801                         | 539                             | 686.62           | 11.44                            |                                  |
|                                          | 1.02                                   | 0.817                         | 557                             | 681.76           | 11.71                            |                                  |
|                                          | 1.01                                   | 0.801                         | 544                             | 692.99           | 11.32                            |                                  |
|                                          | 1.01                                   | 0.801                         | 625                             | 780.27           | 7.96                             |                                  |
|                                          | 1.01                                   | 0.801                         | 634                             | 807.64           | 8.00                             |                                  |
|                                          | 1.01                                   | 0.801                         | 628                             | 784.02           | 7.92                             |                                  |
|                                          | 1.01                                   | 0.801                         | 659                             | 839.49           | 8.39                             |                                  |
|                                          | 1.01                                   | 0.801                         | 648                             | 825.48           | 8.25                             |                                  |
|                                          | 1.01                                   | 0.801                         | 642                             | 817.83           | 8.18                             |                                  |

Table 4. Coefficients of anchoring capacity of the fiber

| Class of concrete | Bottom strength of concrete $f_{c, cube}$, MPa | Prism matrix strength $f_{c, prism}$, MPa | Embedment length $l_e$, mm | The average values of the maximum stresses in the fiber during extraction $\sigma_{fm}$, MPa | Average values of tangential stresses during extraction $\tau_{fm}$, MPa | Coefficient of anchoring ability $\eta_f$ |
|------------------|-----------------------------------------------|---------------------------------------------|-----------------------------|---------------------------------------------|---------------------------------------------|-------------------------------|
|                  |                                               |                                             |                             |                                             |                                             |                               |
| C20/25          | 29.31                                         | 23.15                                       | 10                          | 532.10                                      | 13.37                                       | 0.435                         |
|                  |                                               |                                             | 15                          | 587.10                                      | 9.87                                        | 0.592                         |
|                  |                                               |                                             | 25                          | 692.76                                      | 6.97                                        | 0.835                         |
| C25/30          | 34.76                                         | 27.11                                       | 10                          | 569.70                                      | 14.34                                       | 0.476                         |
|                  |                                               |                                             | 15                          | 638.95                                      | 10.70                                       | 0.636                         |
|                  |                                               |                                             | 25                          | 752.37                                      | 7.57                                        | 0.901                         |
| C30/35          | 38.96                                         | 31.14                                       | 10                          | 606.81                                      | 15.27                                       | 0.513                         |
|                  |                                               |                                             | 15                          | 685.44                                      | 11.52                                       | 0.681                         |
|                  |                                               |                                             | 25                          | 809.12                                      | 8.12                                        | 0.962                         |

For the average values of stresses in the fiber when extracted from concrete of different strength classes, it was found that they are greater, the greater the strength of concrete and the length of laying fiber in concrete is (Figure 4). Therefore, the stress in the fiber during extraction:

$$\sigma_f = 0.4677 \frac{l_e}{d_f} f_{c, prism} + 441.2.$$ (4)
Figure 4. Stress in the fiber $\sigma_f$ depending on the relative length of laying $\frac{L}{d_f}$ and the strength of concrete $f_{\text{prism}}$.

This formula is not valid for fiber laying lengths of less than 10 mm, but indicates that the anchor provides a fiber tension of about 400 MPa when the fiber is pulled out. This effect needs to be studied in further research.

4. Conclusions

According to the results of experimental studies of the adhesion of concrete to the anchor fiber of Ukrainian production and their analysis, the following conclusions can be drawn:

1. With the length of laying the fiber 10, 15 and 25 mm in fine-grained concrete classes C 20/25, C25/30 and C 30/35, the stresses in it do not reach the limit of strength, and all the fiber is pulled out.
2. The stresses in the fiber during stretching increase with increasing strength of concrete and the length of laying fiber into concrete.
3. The end fiber anchors provide a tension in the fiber of about 400 MPa by pulling the fiber. It is necessary to further study the effect of concrete strength on the operation of the end anchors.
4. The coefficient of anchoring ability $\eta$ depends on the length of laying fiber into concrete and the strength of concrete. Therefore, additional justification of the use of this coefficient in the formula to determine the tensile strength of reinforced concrete is needed.

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