STUDY ON SHORT-FIBRE REINFORCED CONCRETE PROPERTIES
ĪSŠĶIEDRU BETONA ĪPAŠĪBU PĒTĪJUMI

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Abstract. In order to develop inexpensive and effective building materials for agricultural buildings, in many cases it is useful to apply short-fibre reinforced concrete. The fibrous reinforcement of concrete matrices improves the tensile strength properties of a composite and imparts to it the qualities of crack control, toughness, ductility and impact resistance as well as the resistance in case of stresses caused by hygro or thermal action. The use of the short-fibre reinforced concrete by applying steel, glass or synthetic fibre in many cases is convenient. The short-fibre is produced applying the second-quality glass fibre and by utilizing the used up steel cables or by milling scrap. The properties of the short-fibre reinforced concrete and the structure of the reinforcement distribution in a material, i.e., the degree of structural anisotropy, essentially depend on the reinforcement properties and the material forming type. The main purpose of this study is to perform experimental estimation of the steel fibre reinforcement distribution in the material and determination of the strength properties as well as the elastic properties with the reinforcement distribution characteristics. The reinforcement arrangement in a solid concrete is determined using the stereological principle and electromagnetic method. The analytical predictions of the elastic properties show a good agreement with the experimentally obtained data. The strength values in the axial tension, splitting and flexure increase with the fibre length and change linearly with the fibre surface area per volume unit of material. The effect of the fibre length and fibre surface area per volume unit is significant in the case of the splitting and flexure. Both these properties characterize material toughness in the case of action of high local pressure and impact loading present in case of floors of agricultural buildings.
Key words: concrete matrix, elasticity, fibrous reinforcement, strength.

1. Introduction

Most efforts to improve the durability of floors in agricultural buildings has focused on improvement the concrete quality using a short-fibre reinforcement of steel, glass or synthetic fibre. Due to the fiber reinforcement the concrete acquires several advantages such as superior crack control, ductility, energy absorption capacity, and increase the tensile strength of the concrete due to the bonding between the fibers and the matrix (R. N. Swamy, 1974). The short-fibre is produced using the second-quality glass fibre and by utilizing the used up steel cables or by milling scrap.

The properties of the short-fibre reinforced concrete and the character of the reinforcement distribution in the material, i.e. the degree of structural anisotropy, essentially depend on the reinforcement properties and the material casting method (mechanical vibration, pressure-cast, vacuum casting, use of fibre carcass). Fiber-reinforced cementitious composites are compouned by matrices that are quasibrittle, by fibers that are relatively ductile, interfaces that can transfer important shear forces between the constituents. In order to improve the toughness of the material, a uniform distribution of the fibre gravity centers is needed.

The purpose of this study is to perform an experimental investigation of the steel fibre reinforcement distribution in the material and determination of the strength characteristics as well as the elastic characteristics in relationship of reinforcement distribution. The reinforcement arrangement in a solid concrete is determined using the stereological principle and electromagnetic method. The analytical prognosis of the elastic properties show a good agreement with the experimentally obtained data.

2. Experimental investigation

In order to determine the effect of the short-fibre reinforcement on strength properties the tests of fiber reinforced concrete (FRC) specimens in axial tension, splitting and flexure were carried out. The distribution of fibres in solid concrete was determined before. The reinforced and plane concrete prisms in axial compression were tested in order to verify an analytical model for determination the strain characteristics of composite material.

Fiber reinforced concrete specimens with randomly oriented short non-galvanized steel fibers were tested in the axial tension and compression as well as in flexure. Three different fiber volume content, V_f, were used: 2 %, 3 %, and 4 %. The diameter of fiber was 0.2...0.35 mm. Fibre length was 20...40 mm. Fibers were cuted to the desired length using a manual table-top cutting machine. Matrix mix proportions were 1/2.5/0.55 by weight of portland cement, fine sand, and water, respectively. Modulus of the wire was 210 GPa and the yield strength was 1.2 GPa. Wire surfaces were cleaned by acetone to remove the oil.

Sand and cement were mixed using the rotating mixer. When the wet mixture had attained a uniform consistency, the fibers were added slowly to prevent bundling and to ensure a random distribution. Wet mixing of the materials was done in 3 min. The specimens were casted into properly oiled steel forms. The vibration time was done for 1 min in order to obtain a uniform compaction. After 24 h the specimens were demolded and cured in a humid room. The specimens were tested at the age of 2 months.

The waisted specimens with cross-section 5x5 cm were tested in the tension. The specimens failed at the weak section soon after the cracking of the mortar. Almost entirely linear relationship between load and deformation were observed up to the cracking stress reached 3.0-3.5 MPa, after that a load drop-off was observed. The strength value of FRC in the axial tension $R_{fb\,t}$ was determineted using the ultimate load. Tensile strains were calculated using the displacements measured by the linear variable differential transformer (LVDT) with a gauge length of 70 mm. In order to determine the splitting strength value $R_{fb\,ct}$ the cubes 4.5x4.5x4.5 cm were splitted in the direction of casting.

The flexure specimens (5x5x54 cm) were simply supported and subjected to the third-point loading. The extreme fibre strains at the mid-span and deflections were measured by LVDT and dial gauges, respectively. The non-linear character of the load-deflection relationships was initiated by the cracking of the matrix, the appearance of the cracks in the middle third of the span was observed during the test. First cracks were visible by the naked eye only when the load was near it's ultimate value. These cracks widened until failure. No crushing in the compression zone of the specimens was observed up to the collapse. The strength value of FRC in flexure $R_{fb\,tb}$ was determined as a tensile stress at the ultimate load. In order to compare the strength of reinforced concrete with the strength of plain concrete, specimens without fibre reinforcement were casted and tested. The strength values in the axial tension $R_{b\,t}$, splitting $R_{b\,ct}$ and flexure $R_{b\,tb}$ of plain concrete specimens was experimentally determined.

3. Estimation of fibre orientation

The orientation of steel fibre is generally influenced by such factors as the direction of casting, method of compacting, size of specimen, size and volume content of steel fibre, and mix proportions of the matrix concrete (B. Maidl, 1991; J. Brauns, K. Rocens, 1995). The stereological approach (K. Kanatani, 1984) was used for the determination of the structural anisotropy of a composite. After mechanical testing of the specimens and from standard cubes 20x20x20 cm, small testing cubes 4.5×4.5×4.5 cm were cutted out. On new surfaces the number of fibre intersections per area unit for each different orientation of the cutting plane was counted. These observed data characterised the distribution density of fibers and the internal structure of the composite. The measurement of such density was impractical, and, in many cases, impossible. The stereological procedure gave an indirect way of the estimation of that density.

In order to determine the degree of technological anisotropy, horizontal (*xy*) and vertical (*xz*) and (*yz*) planes of the reinforced concrete cubes were examined. The axis *z* was directed in the vertical (casting) direction. For volume content of steel fibre , e.g. V_f =2 %, the mean values of fibre intersections number were $n_{xz,\ m}=20$, $n_{yz,\ m}=21$, $n_{xy,\ m}=14$ and standard deviation values 7.03, 7.62, 7.18, respectively. Figure 1 shows the distribution of the examined areas number with respect to the fibre number per area unit and Gauss distribution curves for horizontal and vertical planes. It is concluded by statistical analysis that the mean values are equal in the vertical planes and differ from those in the horizontal plane.

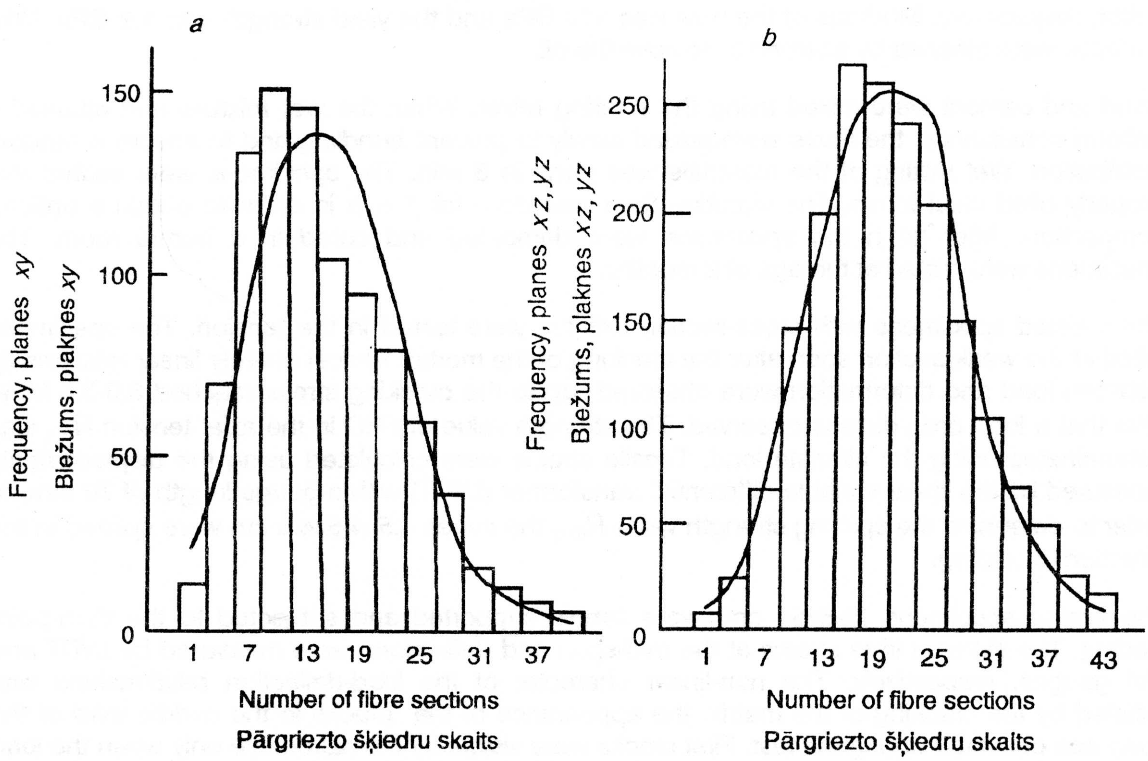


Fig. 1. Histograms and Gauss distribution curves of examined areas number with fibre intersection number per area unit: a - horizontal planes, b - vertical planes.
1. att. Apsekoto laukumu skaita histogrammas atkarībā no pargriezto šķiedru skaita laukuma vienībā un Gausa sadalījuma līknes: a - horizontālās plaknes, b - vertikālās plaknes.

The ferromagnetic method for determination of fiber distribution was applied as well. The method is based on the principle that a body with ferromagnetic properties changes the coil inductance. It is possible to determine the volume of the ferromagnetic inclusion by registering the increase of the induced voltage and in the case of low steel fiber content the relative fiber orientation can be fixed. The experimental distribution function of the reinforcement relative density with respect to the direction for steel fibre reinforced concrete in the vertical plane and approximation at different content of the reinforcement is shown in Fig. 2. Note that the ratio of relative indices in the vertical and horizontal directions for both methods is about 3:2.

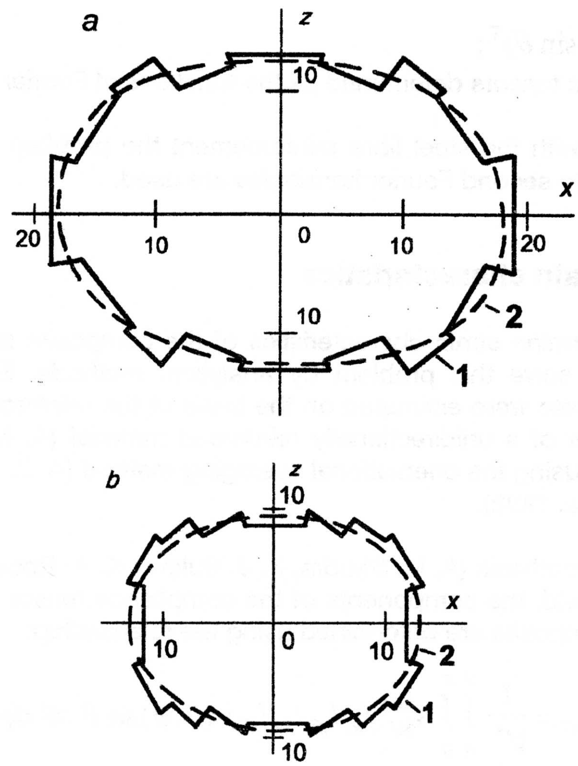


Fig. 2. Fabric functions of steel fibre reinforcement: a - for V_f=2.5 %, b - for V_f=1.0 %;
1 - experimental distribution, 2 - approximation diagram.
2. att. Tērauda šķiedru tekstūras funkcijas: a - pie V_f =2.5 %, b - pie V_f =1.0 %;
1 - eksperimentālais sadalījums, 2 - approksimācijas diagramma.

4. Description of fibre orientation

There is constructed the fabric function of the reinforcement $v(\theta,\ \varphi)=v^{(k)}$ on the basis of the observed data, i.e. the number of intersections or relative electromagnetic indexes. This function characterizes the variation in the calculation volume of the k-th direction of the reinforcement, on the assumption that the reinforcement does not vary with direction, i.e., $V_f^{(k)} = V_f =$ const.

The function $v(\theta,\ \varphi)$ is expressed as a spherical harmonics expansion:

$$v(\theta,\varphi)=\frac{C}{4\pi}[1+\sum_{n=2}^{N}\{\frac{1}{2}A_{n0}P_n(\cos\theta)+\sum_{m=1}^{n}P_n^m(\cos\theta)[A_{nm}\cos m\varphi+B_{nm}\sin m\varphi]\}], \qquad (1)$$

where coefficients C, A_{nm} and B_{nm} are found according to the theory of Fourier series using the least square error approximation;
θ, φ are spherical coordinates of structural element of composite.

The Fourier series expansion can be expressed as a Cartesian fabric tensor equation (plane case) invariant to coordinate transformations

$$v(\mathbf{r})=\frac{C}{2\pi}(1+D_{ij}r_ir_j+D_{ijkl}r_ir_jr_kr_l+\ldots), \qquad (2)$$

$$(i,j=1,2)$$

where vector $\mathbf{r} = (\cos\theta, \sin\theta)^{\mathrm{T}}$;

C, D_{ij}, and D_{ijkl} are fabric tensors determined as the functions of Fourier expansion coefficients.

In the case of concrete with the steel fibre reinforcement the problem is two-dimensional, and anisotropy is "weak", up to second Fourier harmonics are used.

5. Discussion on strain characteristics

It is very difficult to determine strain characteristics of the composite material directly from the experiment. We should solve this problem by analytical methods. Elastic characteristics of spatially reinforced concrete were estimated on the basis of the reinforcement theory for finding elastic compliance tensor of a unidirectionally reinforced material (A. M. Skudra, F. J. Bulavs, K. A. Rocens, 1975) and using the orientational averaging method (A. Ž. Lagzdinš, V. P. Tamužs, G. A. Teters, A. F. Krēgers, 1992).

On the basis of Reuss hypothesis (A. M. Skudra, F. J. Bulavs, K. A. Rocens, 1975) regarding the uniformity of the stress field, the components of the compliance tensor (the lower limit of strain characteristics) of the composite are determined using the relationship:

$$a_{\alpha\beta\gamma\delta} = \frac{1}{V^*} \int_0^{\pi} \int_0^{\pi} a_{ijkl}^{(k)}\, l_{i\alpha}\, l_{j\beta}\, l_{k\gamma}\, l_{l\delta}\, v(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \qquad (3)$$

$(i, j, k, l = x, y, z;\ \alpha, \beta, \gamma, \delta = 1, 2, 3)$,

where $l_{i\alpha}$ are the cosines of the angles between the composite axis and the axis of structural element of the given direction k;

$a_{ijkl}^{(k)}$ - the elastic compliance tensor of a unidirectionally reinforced structural element.

The value V^* *is*

$$V^* = \int_0^{\pi} \int_0^{\pi} v(\theta,\varphi) \sin\theta \, d\theta \, d\varphi .$$

In a similar way, the rigidity tensor is found using the assumption of uniformity of the strain field (Voigt method).

6. Results and discussion

In order to fix the effect of steel fibre reinforcement on the elastic properties of a composite, the theoretical line, characterizing the variation of the composite modulus of elasticity E_x^c (in perpendicular direction to the casting) in relation to concrete (matrix) modulus E_x^m, and experimental results are compared in Fig. 3. The increase of the elastic modulus of FRC is about 3 % per one percent of short-fibre reinforcement. The mean values of elastic modulus (E_x^c, E_x^m) were determined on the basis of results of 3...5 tests; the standart deviation was 0.19...0.54 MPa, coefficient of variation value 7...21 %.

The strength properties of reinforced concrete depend on the effective fibre length and orientation as well as the spacing between the gravity centers of fibers (assuming a uniform fiber distribution in a material). Rupture ratio of the fibre reinforced concrete in axial tension is analysed. The variation of strength characteristics with respect to the total fibre surface area in volume unit of the material $A_{fs} = 4V_f/d_f$ is shown in Fig. 4. It can be seen that disregarding the fibre diameter d_f the efficiency of the reinforcement increases proportionally to fibre length l_f. Similar relationship is fixed by testing cubes in splitting (Fig. 5).

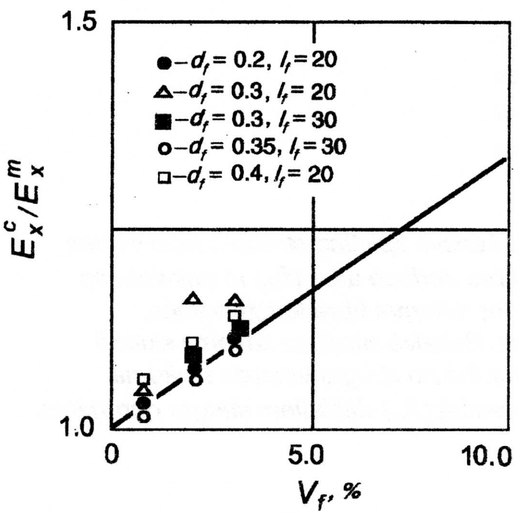
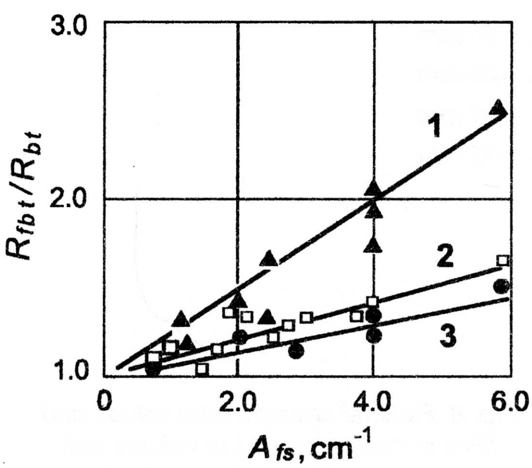


Fig. 3. Predicted increase of modulus of composite material and volume content of reinforcement for different values (mm) of fiber diameter (d_f) and length (l_f).
3. att. Stiegrota betona prognozētā elastības moduļa palielināšanās atkarībā no stiegrojuma daudzuma dažādiem stiegru diametra (d_f) un garuma (l_f) lielumiem (mm).



1 - l_f =10 mm
2 - l_f =20 mm
3 - l_f =30 mm

Fig. 4. Ratio of tensile strength values and fibre surface area (A_{fs}) in volume unit for different fibre length values.
4. att. Stiprības robežas lielumu izmaiņa centriskā stiepē atkarībā no stiegru virsmas laukuma tilpuma vienībā (A_{fs}) dažādiem stiegru garumiem.

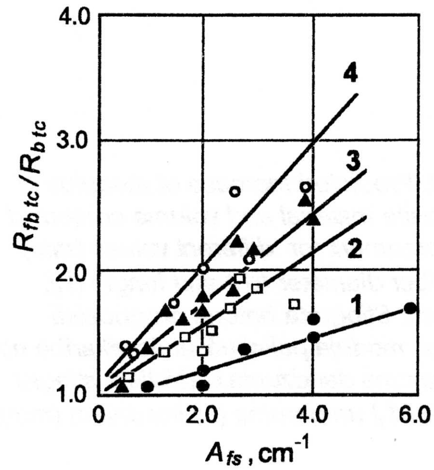
More significant increase of flexural strength is observed (Fig. 6). On the basis of relationships showed in Fig. 4 to Fig. 6 it can be concluded that the fibre length l_f=40 mm and the fibre content V_f=3 % are the optimum values of the reinforcement, providing the maximum strength increase of a composite. At the same time they are the limiting values for the given casting technology and mechanical vibration.

The strength values in axial tension, splitting and flexure increases proportional to the fibre length and the fibre surface area per unit material volume. The effect of the mentioned reinforcement characteristics is significant in the case of the splitting tension and flexure. These both properties characterize the material toughness in the case of action of high local pressure and impact loading on floors in agricultural buildings in particular.

The influence of the fiber spacing and the length values on flexural strength was investigated. Assuming a uniform distribution of the fiber gravity centers in space the fiber spacing s was calculated by the formula:

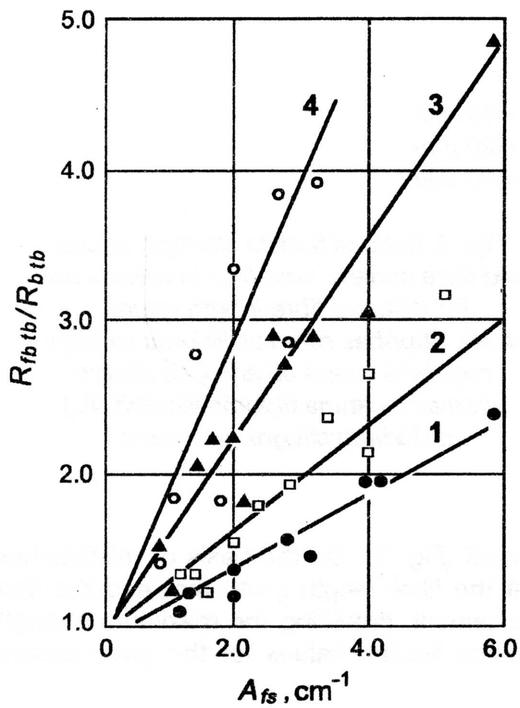
$$s=\sqrt[3]{\frac{\pi d_f^2 l_f}{4V_f}}.$$

The experimental relationships of flexural strength ratio and spacing between the fibres are shown in Fig. 7. The increase of flexural strength in relationship of the fibre length is essential. It can be seen in Fig. 7 that for each fibre spacing value the flexural strength ratio changes about two times by increasing the fibre length 2 times.



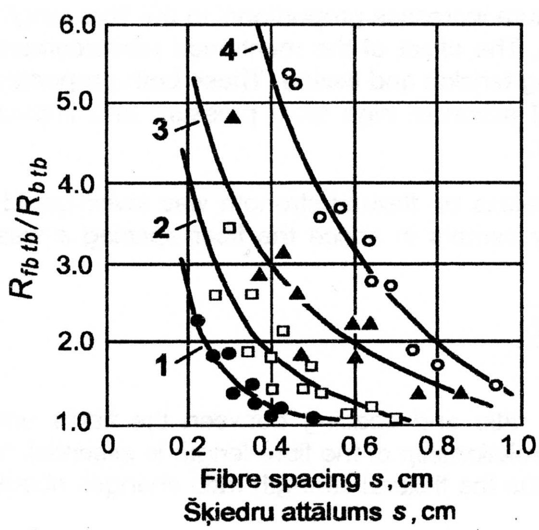
1 - l_f =10 mm
2 - l_f =20 mm
3 - l_f =30 mm
4 - l_f =40 mm

Fig. 5. Tensile splitting strength ratio values and fibre surface area (A_{fs}) in unit volume for different fibre length values.
5. att. Relatīvā stiprības izmaiņa skaldē atkarībā no stiegru virsmas laukuma tilpuma vienībā (A_{fs}) dažādiem stiegru garumiem.



1 - l_f =10 mm
2 - l_f =20 mm
3 - l_f =30 mm
4 - l_f =40 mm

Fig. 6. Flexural strength ratio values and fibre surface area (A_{fs}) in volume unit for different fibre length values.
6. att. Relatīvā stiprības izmaiņa liecē atkarībā no stiegru virsmas laukuma tilpuma vienībā (A_{fs}) dažādiem stiegru garumiem.



1 - l_f =10 mm
2 - l_f =20 mm
3 - l_f =30 mm
4 - l_f =40 mm

Fig. 7. Flexural strength ratio values and fibre spacing (s) for different fibre length values.
7. att. Relatīvā stiprības izmaiņa liecē atkarībā no attāluma starp stiegrām (s) dažādiem stiegru garumiem.

7. Conclusions

1. Experimental estimation of steel fibre reinforcement distribution in a material and determination of the strength characteristics as well as the elastic properties with reinforcement distribution characteristics was performed.

2. On the basis of the orientational averaging method and by using the reinforcement theory for finding the elastic compliance tensor of a unidirectionally reinforced structural element, elastic properties of spatially reinforced concrete were estimated. The analytical prediction of elastic properties showed a good agreement with the experimentally obtained data.

3. The strength values in the axial tension, splitting tension and flexure increased with the fibre length and changed linearly with the fibre surface area per unit of material volume. The effect of the fibre length and the total fibre surface area per volume unit was significant in the case of the splitting and flexure.

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ANOTĀCIJA

Lauksaimniecības mašīnu remonta un uzglabāšanas ēkās grīdas ir pakļautas lielu koncentrētu slodžu iedarbībai. Lai panāktu šo grīdu atbilstību funkcionālām un iestrādāšanas prasībām, kā arī lai iegūtu noteiktu ilgizturību pret dilšanu un triecienslodzēm, tās var veidot no īsšķiedru betona (dispersi stiegrots betons). Šāda betona stiegrošanai iespējams izmantot otrreizējās izejvielas - nekondīcijas stikla šķiedras, sagrieztas nolietotas tērauda troses, no pārkausētiem metāllūžņiem frēzētas īsšķiedras. Īsšķiedru stiegrojums paaugstina betona stiepes stiprību, triecienstigrību, pretestību higrotermiskām iedarbībām un uzlabo citas fizikāli mehāniskās īpašības. Dispersās stiegrošanas metodes dod iespēju realizēt telpisko stiegrojumu un plaknisko stiegrojumu, kur stiegras orientētas vienā plaknē (ar patvaļīgu vai noteiktu orientāciju).

Patreiz pasaulē izstrādā dažāda veida dispersi stiegrotās konstrukcijas. Piemēram, ASV un Lielbritānijā betonu ar īsšķiedru stiegrojumu pielieto vairāk nekā 100 firmas. Telpisko stiegrojumu lieto pāļu galu nostiprināšanai, bet plakniskais stiegrojums realizējas plānsienu konstrukcijās. Visizplatītākās šāda tipa konstrukcijas ir ceļu un aerodromu plātnes, ražošanas ēku grīdas, liela izmēra zemspiediena caurules, nenoņemamie veidņi, renes, rezervuāri u.c.

Izgatavošanas tehnoloģija būtiski ietekmē dispersi stiegroto materiālu īpašības. Dispersi stiegroto betonu var gatavot pēc diviem tehnoloģiskiem paņēmieniem - īsšķiedru sajaukšana ar betona komponentēm tieši maisīšanas procesā un stiegru pievienošana sagatavotai betona masai.

Iestrādājot betona masu ar tradicionālo vibrināšanas paņēmienu, smaguma spēka un berzes iespaidā notiek šķiedru orientēšanās, kas rada stiegrojuma struktūras tehnoloģisko anizotropiju.

Darbā veikta pēc noteiktas tehnoloģijas iestrādāta betona īsšķiedru stiegrojuma izvietojuma struktūras izpēte un analīze. Stiegru orientācija materiālā noteikta ar stereoloģiskās un elektromagnētiskās metodes palīdzību. Izpētot īsšķiedru izvietojumu betonā un veicot stiegrojuma tekstūras funkcijas analītisku aprakstu, noteiktas materiāla deformatīvās īpašības, kas salīdzinātas ar eksperimenta rezultātiem. Deformatīvo raksturlielumu noteikšanai izmantota vidējotās orientācijas metode. Noteikti īsšķiedru betona stiprības raksturlielumi stiepē, skaldē, liecē atkarībā no stiegru telpiskā izvietojuma un to ģeometriskajiem raksturlielumiem. Ar īsšķiedrām stiegrota betona pretestība stiepē, skaldē, liecē netieši raksturo materiāla stigrības īpašības, kas ir būtiski svarīgas vietējo statisko un trieciensłodžu gadījumā, un pierāda šī materiāla izmantošanas iespējas lauksaimniecības ēku grīdās. Iegūtie rezultāti dod iespēju prognozēt stiprības īpašības nekondīcijas šķiedru gadījumā, kad tiek izmantotas otrreizējās un vietējās izejvielas.