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Selection of Optimal Formation Parameters of Polypropylene Fibrillated Fibres Designed for Concrete Reinforcement

Abstract
For the reinforcement of concrete, fibrillated polypropylene fibres are used. The effectiveness of the reinforcement depends on the fibre geometry as well the mechanical parameters. The production of fibrillated fibres is a multistage process in which formation conditions exert a great influence on the final properties of the fibres. Fibrillated polypropylene fibres were produced by different formation parameters. Mechanical parameters of the fibres: tenacity, elongation at break, and Young modulus were measured. Results of the measurements were analysed by statistical methods. On the basis of the analysis performed, beneficial formation parameters were established.

Key words: *polypropylene, fibrillated fibres, formation parameters, mechanical parameters, statistical analysis.*

Introduction

For many years fibres have been used for the reinforcement of concrete [1 - 5]. The addition of short fibres effectively reduces the spread of shrinkage cracks and has a positive impact on concrete parameters. Fibre-reinforced concrete is more and more widely used for the construction of roads and highways, airports, watersides and many other engineering objects. Due to their beneficial properties, polypropylene fibres are a subject of particular interest [6, 7]. For the reinforcement of concrete different polypropylene fibres are offered. The offer comprises staple monofilaments, multifilaments, fibrillated fibres as well as other deformed fibres. These fibres are produced from pure polypropylene or polypropylene copolymers. Their geometry as well as surface and mechanical properties influence the effectiveness of the reinforcement [8]. Fibrillated fibres and those deformed by crimping or twisting possess better adhesive capacity to the cementitious matrix. Especially fibrillated fibres seem to have a distinct advantage [5] as they form an open network, which will increase the specific surface area. As a result the adhesion of fibres to the cement matrix is considerably improved.

Fibrillated fibres are produced by splitting narrow polypropylene strips, The formation of fibrillated polypropylene fibres is a multistage process and involves melt extrusion through a flat or annular die, film solidification through water quenching or air cooling, uniaxial stretching of the film, heat stabilisation, cutting the film into narrow tapes, splitting the tapes into finer fibrous material and final take-up [9 - 11]. Each step exerts a great influence on the fibre structure and their final properties [12]. The choice of proper formation conditions has great significance. The optimal selection of formation parameters enables the production of fibres with good mechanical properties, which are greatly demanded for concrete reinforcement. This paper presents the results of investigations of the mechanical properties of fibrillated fibres designed for concrete reinforcement. Fibrillated fibres were produced and their mechanical parameters in the function of certain formation parameters were measured. The results obtained were analysed by statistical methods. On the basis of the analysis, optimal parameters for the production of fibrillated fibres were established.

Experimental

Samples

Fibres were produced in industrial conditions using a Starlinger StarEx 1500 production line. Polypropylene films were extruded through a flat die into water. Solidified films were then cut into narrow strips. After drawing and heat stabilisation, strips were locally cut with a needle roller and split with the final stretching unit.

The fibres were produced with the following parameters:
- temperature of heating zones of the extruder - 250 °C,
- extrusion velocity - 14 m/min,
- film thickness - 152 μm,
- film width - 1485 mm,
- strip width - 87 mm,
- temperature of stabilisation - 120 °C.

Fibres with a linear density of 1000 tex were produced. Two draw ratios: 10 and 12 and four velocities of the needle roller: 155, 175, 195 and 215 m/min were applied.

Commercial polypropylene resin Moplen HP 456J (Orlen Polyolefins) characterised by a melt flow index of 3.4 g/10 min was used. Fibres were also produced with the addition of a small amount (2% by weight) of polyethylene Bralen FB 2- 30 (Slovnaft Petrochemicals)

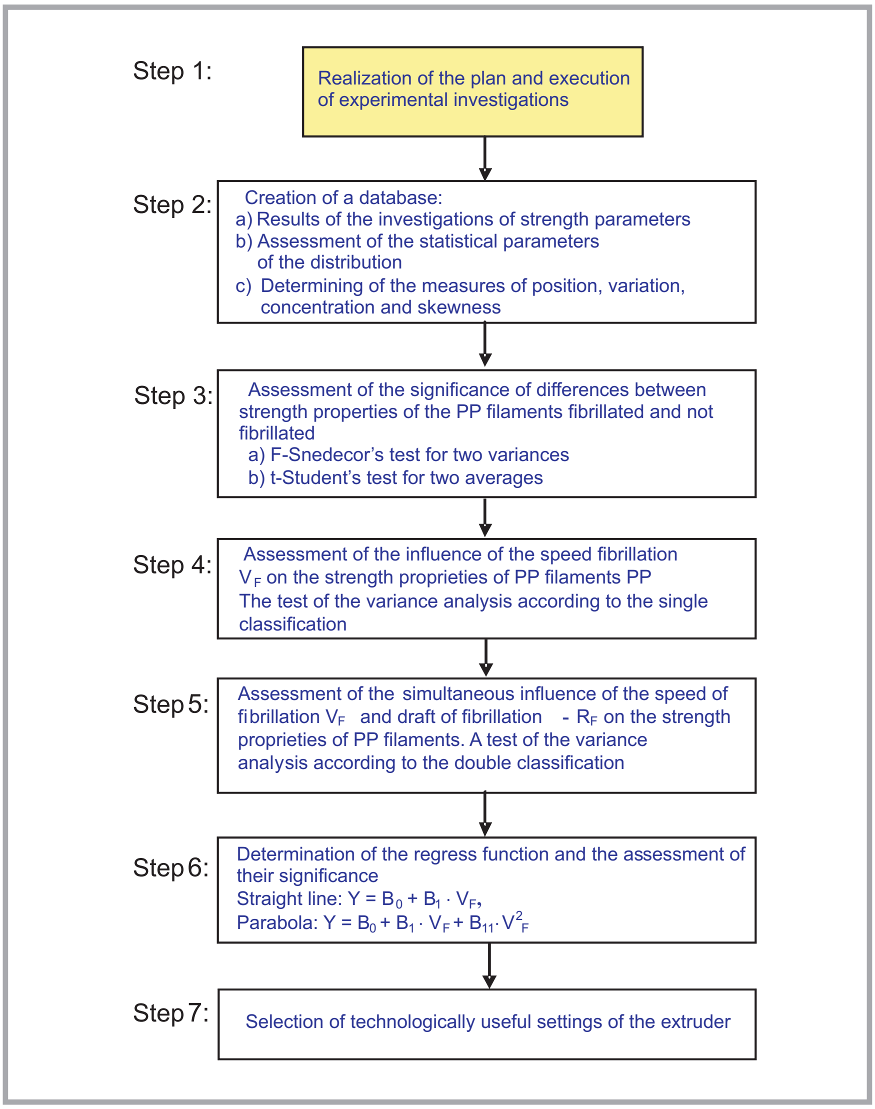

***Figure 1**. Algorithm of modelling the fibrillation process of polypropylene fibres.*

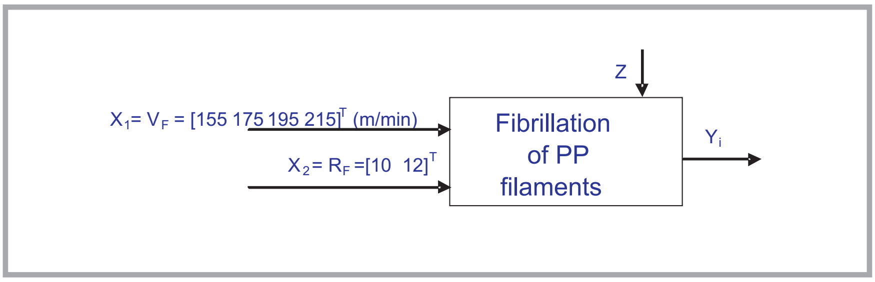

***Figure 2.** Plan of experimental investigations; X_1 = V_F (m/min) – needle roller velocity, X_2 = R_F – draw ration of fibrillation, Z – non-measurable disturbances of fibrillation process.*

Methods

For the fibres, the following mechanical parameters were determined: tenacity, elongation at break and Young modulus. The measurements were performed according to Standard PN-EN ISO 5079: 1999 using the tensile machine INSTRON 1026. Analysis of the results was carried out according to the algorithm presented in ***Figure 1***.

For every parameter analysed, the basic statistical parameters were calculated. For evaluation of the influence of the needle roller velocity on the mechanical parameters of the fibres, the t-Student test for two averages was applied. The test was preceded by the F-Snedecor's test. Using this test, the degree of dispersion of the parameters measured was determined. Furthermore, using variance analysis according to the single classification, the influence of the roller velocity V_F on the mechanical parameters: tenacity, elongation at break and Young modulus was examined [14, 15]. The simultaneous influence of the needle roller velocity V_F and draw ratio R_F on the mechanical parameters of the fibres was evaluated by a test of the variance analysis according to the double classification [14, 15]. For the assessment of the influence of the needle roller velocity V_F on the mechanical parameters of the fibres, functions of the regress were used, approximated by a straight line and parabola according to equations:

$$\hat{Y} = B_0 + B_1 \cdot V_F\ , \quad (1)$$

$$\hat{Y} = B_0 + B_1 \cdot V_F + B_{11} \cdot V_F^2\ , \quad (2)$$

where:

$\hat{Y}_i$ – value of the regress function of *i*-th parameter of the fibrillated fibres,

$[B_0; B_1; B_{11}]^T$ – vector of the coefficient of the regress function,

V_F – needle roller velocity.

For each function the coefficient of the multiple correlation of regress R_W was determined and its significance checked [14, 15].

Results

Step 1. Realisation of the plan and execution of experimental investigations

A plan of the experimental investigations is presented in ***Figure 2.***

Step 2. Creation of the database: a) Results of the investigations of strength parameters, b) Assessment of the statistical parameters of the distribution, c) Determination of the measures of position, variation, concentration and skewness

The values of the tenacity W_t of the fibres measured for a draw ratio of 10 and 12 are presented in ***Tables 1*** and ***2***.

Analysing the results of the investigations, presented in ***Tables 1*** and ***2***, one can notice that:

- larger values of the tenacity W_t are shown by fibres drawn at ratio R_F = 12,
- the two largest values of tenacity W_t are demonstrated by fibres fibrillated at V_F = 155 m/ min (W_t = 47.97 cN/tex)

and V_F = 175 m/min (W_t = 47.66 cN/tex),
- the most beneficial, i.e. the smallest power of the coefficient of variation of the tenacity $V(W_t)$ = 2.76% is shown by the fibres fibrillated at V_F = 155 m/min and R_F = 12,
- the most beneficial value of skewness A_s = -0,004 is demonstrated by the fibres fibrillated at V_F = 195 m/min and R_F = 12,
- the most beneficial value of kurtosis is shown by fibres fibrillated at V_F = 215 m/min and R_F = 10 (K = 0,24) and V_F = 155 m/min and R_F = 12 (K = 1,64).

Tables 3 and ***4*** present the values of elongation at break ε_r measured.

Analysing the values of elongation at break ε_r one can state that:
- larger values of the elongation at break are exhibited by fibres drawn at ratio R_F = 10,
- the two largest values of elongation at break are demonstrated by fibres fibrillated at V_F = 195 m/ min (ε_r = 24.94%) and V_F = 215 m/min (ε_r = 25.28%),
- the most beneficial, i.e. the smallest power of the coefficient of the variation in the elongation at break $V(\varepsilon_r)$ is shown by fibres fibrillated at V_F = 175 m/min and R_F = 10 ($V(\varepsilon_r)$ = 6.02%) and V_F = 195 m/min ($V(\varepsilon_r)$ = 6.72%),
- the most beneficial value of the skewness A_s = -0.21 is demonstrated by fibres fibrillated at V_F = 175 m/min and R_F = 10,
- the most beneficial value of kurtosis K is demonstrated by PP filaments fibrillated at V_F = 215 m/min and draft R_F = 10 (K = -0.02) and also V_F = 155 m/min and draft R_F = 12 (K = 0.58).

Tables 5 and ***6*** (see page 72) present the values of Young modulus E measured.

Analysing the results of Young modulus – E, one can notice that:
- larger values of Young's modulus E are shown by fibres drawn at ratio R_F = 12,
- the two largest values of Young's modulus E are demonstrated by fibres fibrillated at V_F = 155 m/ min (E = 3.55 cN/tex) and V_F = 175 m/min (E = 3.20 cN/tex) ,
- the most beneficial, i.e. the smallest power of the coefficient of the varia-

Table 1. *Breaking tenacity – W_t of fibres drawn at ratio R_F = 10.*

Parameter analysed	Unit	Needle roller velocity – V_F, m/min				Not fibrillated
		155	175	195	215	
Mean value	cN/tex	42.30	41.70	41.43	38.95	47.24
Standard deviation	cN/tex	1.48	1.66	1.55	1.40	2.26
Coefficient of variation	%	3.49	3.97	3.74	3.59	4.79
Absolute error	cN/tex	0.55	0.62	0.58	0.52	0.85
Relative error	%	1.30	1.48	1.40	1.34	1.79
Minimum value	cN/tex	39.40	39.60	37.80	35.53	42.36
Maximal value	cN/tex	44.60	46.00	43.70	41.58	51.20
Median	cN/tex	42.29	41.25	42.00	38.96	47.43
Kurtosis	–	-0.73	0.61	-0.41	0.24	-0.61
Skewness	–	-0.33	0.96	-0.61	-0.17	-0.25

Table 2. *Breaking tenacity – W_t of fibers drawn at ratio R_F = 12.*

Parameter analyzed	Unit					Not fibrillated
			175	195	215	
Mean value	cN/tex		47.66	42.49	41.15	51.02
Standard deviation	cN/tex		1.64	1.36	1.56	1.55
Coefficient of variation	%		3.45	3.20	3.80	3.03
Absolute error	cN/tex		0.61	0.51	0.58	0.58
Relative error	%		1.29	1.19	1.42	1.13
Minimum value	cN/tex		44.16	39.39	38.42	47.24
Maximal value	cN/tex		50.51	45.00	44.60	53.92
Median	cN/tex		47.84	42.57	41.24	50.63
Kurtosis	–		-0.47	0.02	-0.40	0.25
Skewness	–		-0.35	-0.04	0.21	-0.04

Table 3. *Elongation at break – ε_r of fibres drawn at ratio R_F = 10.*

Parameters analyzed	Unit	Needle roller velocity – V_F, m/min				Not fibrillated
		155	175	195	215	
Mean value	%	24.67	24.83	24.94	25.28	29.52
Standard deviation	%	2.17	1.49	1.68	3.42	2.46
Coefficient of variation	%	8.80	6.02	6.72	13.55	8.35
Absolute error	%	0.81	0.56	0.63	1.28	0.92
Relative error	%	3.28	2.25	2.51	5.06	3.12
Minimum value	%	21.25	22.50	22.50	22.25	24.38
Maximal value	%	28.75	27.50	28.75	32.50	35.00
Median	%	24.07	25.00	24.38	23.75	29.38
Kurtosis	–	-0.49	-1.18	-0.54	-0.02	-0.36
Skewness	–	0.33	-0.20	0.62	1.13	0.18

Table 4. *Elongation at break – ε_r of fibres drawn at ratio R_F = 12.*

Parameter analysed	Unit	Needle roller velocity – V_F, m/min				Not fibrillated
		155	175	195	215	
Mean value	%	22.84	23.15	21.56	21.48	26.13
Standard deviation	%	1.98	2.14	2.14	2.84	2.27
Coefficient of variation	%	8.68	9.26	9.92	13.23	8.69
Absolute error	%	0.74	0.80	0.80	1.06	0.85
Relative error	%	3.24	3.46	3.70	4.94	3.24
Minimum value	%	20.00	20.00	18.75	17.00	22.50
Maximal value	%	27.50	27.50	26.25	27.50	30.00
Median	%	22.50	22.50	21.25	20.63	25.32
Kurtosis	–	0.58	-0.82	-0.41	-0.22	-0.82
Skewness	–	1.03	0.27	0.76	0.73	0.47

Table 5. Young modulus – E of fibrillated fibres drawn at ratio R_F =10.

Parameter analysed	Unit	Needle roller velocity – V_F, m/min				Not fibrillated
		155	175	195	215	
Mean value	cN/tex	2.61	2.55	2.70	2.40	2.73
Standard deviation	cN/tex	0.27	0.33	0.14	0.39	0.25
Coefficient of variation	%	10.39	12.77	5.25	16.11	9.33
Absolute error	cN/tex	0.10	0.12	0.05	0.14	0.09
Relative error	%	3.88	4.77	1.96	6.02	3.48
Minimum value	cN/tex	2.09	1.56	2.26	1.70	2.08
Maximal value	cN/tex	3.03	2.98	2.86	3.10	3.17
Median	cN/tex	2.64	2.66	2.74	2.40	2.78
Kurtosis	–	-0.97	2.31	1.94	-0.88	0.24
Skewness	–	-0.19	-1.52	-1.36	-0.17	-0.31

Table 6. Young modulus – E of fibrillated fibres drawn at ratio R_F =12.

Parameter analysed	Unit	Needle roller velocity – V_F, m/min				Not fibrillated
		155	175	195	215	
Mean value	cN/tex	3.55	3.20	3.14	2.95	2.98
Standard deviation	cN/tex	0.40	0.30	0.32	0.44	0.36
Coefficient of variation	%	11.34	9.33	10.33	14.90	12.10
Absolute error	cN/tex	0.15	0.11	0.12	0.16	0.13
Relative error	%	4.23	3.48	3.86	5.56	4.52
Minimum value	cN/tex	3.04	2.69	2.37	2.03	2.20
Maximal value	cN/tex	4.40	4.02	3.60	3.76	3.70
Median	cN/tex	3.46	3.20	3.17	2.94	2.97
Kurtosis	–	-0.22	0.77	-0.05	-0.27	-0.15
Skewness	–	0.78	0.50	-0.60	-0.30	-0.11

Table 7. Values calculated for F-Snedecor's and t-Student's tests.

V_F, m/min	Item number	Parameter of fibres analysed	R_F = 10				R_F = 12			
			F-Snedecor's test, α = 0.05		t-Student's test, α = 0.05		F-Snedecor's test, α = 0.05		t-Student's test, α = 0.05	
			$F_{calc.}$	$F_{crit.}$	$t_{calc.}$	$t_{crit.}$	$F_{calc.}$	$F_{crit.}$	$t_{calc.}$	$t_{crit.}$
155	1	Tenacity	1.60		14.48		1.36		8.21	
	2	Elongation at beak	2.56	1.86	13.09	2.00	1.31	1.86	5.98	2.00
	3	Young modulus	2.57		18.08		1.24		5.77	
175	1	Tenacity	2.16		8.42		1.13	1.86	8.15	
	2	Elongation at beak	2.72	1.86	8.91	2.00	1.12	1.86	5.23	2.00
	3	Young modulus	1.93		5.51		1.45	1.86	2.65	
195	1	Tenacity	2.14		11.59		1.29		22.68	
	2	Elongation at beak	1.87	1.86	10.81	2.00	1.13	1.86	8.01	2.00
	3	Young modulus	2.62		17.06		1.23		1.88	
215	1	Tenacity	3.24		0.59		1.02		24.57	
	2	Elongation at beak	1.64	1.86	2.33	2.00	1.57	1.86	6.99	2.00
	3	Young modulus	2.31		3.87		1.49		0.21	

Table 8. Results of the test of the variance analysis according to the single classification.

Draw ratio: R_F	Item number	Parameter analysed	Values of F-Snedecor's test, α = 0.05	
			$F_{calc.}$	$F_{crit.}$
10	1	Tenacity	28.122	
	2	Elongation at break	0.368	2.683
	3	Young modulus	5.319	
12	4	Tenacity	168.255	
	5	Elongation at break	4.160	2.683
	6	Young modulus	13.262	

tion in the Young modulus (V(E) = 9.33%) is shown by fibres fibrillated at V_F = 175 m/min and R_F = 12,

- the most beneficial value of skewness A_s is demonstrated by fibres fibrillated at V_F = 175 m/min and R_F = 10 (A_s = -1.36) and also V_F = 175 m/min and R_F = 12 (A_s = -0.60)
- the most beneficial value of kurtosis K is demonstrated by fibres fibrillated at V_F = 175 m/min and R_F = 10 (K = 2.31).

Step 3. Assessment of the significance of differences between strength properties of PP filaments fibrillated and not fibrillated; a) F-Snedecor's test for two variances, b) t-Student's test for two averages

Table 7 presents values calculated for the F-Snedecor's and t-Student's tests.

Analysing the results of the tests, one can conclude that all the mechanical parameters of the fibrillated fibres differ in a statistically essential way from those of the not fibrillated fibres.

Step 4. Assessment of the influence of the speed fibrillation -V_F on the strength proprieties of PP filaments PP; Test of the variance analysis according to the single classification

Table 8 presents values calculated for the test of the variation analysis according to the single classification.

Analysis of the results of the test shows that:

- at draw ratio R_F = 10 the change in tenacity W_t and Young modulus E of the fibrillated fibres caused by a change in the needle roller velocity V_F is larger than that produced by non-measurable disturbances of the fibrillation process. The changes in needle roller velocity V_F do not influence significantly the value of elongation at break ε_r.
- at draw ratio R_F = 12 the change in all parameters measured produced by a change in needle roller velocity V_F is larger than that produced by non-measurable disturbances of the fibrillation process.

Step 5. Assessment of the simultaneous influence of the speed of fibrillation V_F and draft of fibrillation - R_F on the strength proprieties of PP filaments. Test of the variance analysis according to the double classification

***Table 9.** Results of the test of the variance analysis according to the double classification; $F_{V,\alpha}$ – calculated value of F-Snedecor statistics, $F_{R,\alpha}$ – calculated value of F-Snedecor statistics, $F_{1crit.}$ = 10.128 – critical values of F-Snedecor statistics determined for r_1 = 1 and r_2 = 3 degrees of freedom at t significance level - α = 0.05, $F_{2crit.}$ = 9.277 – critical values of F-Snedecor statistics determined for r_1 = 3 and r_2 = 3 degrees of freedom at significance level - α = 0.05.*

Item number.	Parameter analysed	Needle roller velocity V_F		Draw ratio R_F	
		$F_{V,\alpha}$	$F_{1crit.}$	$F_{R,\alpha}$	$F_{2crit.}$
1	Tenacity	9.133	10.128	3.765	9.277
2	Elongation at break	**24.850**		0,406	
3	Young modulus	**37.430**		2,449	

***Table 10.** Setting-up of statistical parameters of the distribution of analyzed strength proprieties of the fibrillated PP filaments chosen for the selection of optimum parameters.*

Parameters analysed	Symbol	Unit	Most beneficial formation parameters	
			Needle roller velocity – V_F, m/min	Draw ratio – R_F, –
Tenacity	$\overline{W_t}$	cN/tex	155	12
Elongation at break	$\overline{\varepsilon_r}$	%	215	10
Young modulus	$\overline{E}$	cN/tex	155	12
Coefficient of variation of tenacity	$V(\overline{W_t})$	%	155	12
Coefficient of variation of elongation at break	$V(\overline{\varepsilon_r})$	%	175	10
Coefficient of variation of Young modulus	$V(\overline{E})$	%	195	10
Skewness of tenacity	$A_s(W_t)$	–	195	10
Skewness of elongation at break	$A_s(\varepsilon_r)$	–	175	10
Skewness of Young modulus	$A_s(E)$	–	175	10
Kurtosis of tenacity	$K(W_t)$	–	155	12
Kurtosis of elongation at break	$K(\varepsilon_r)$	–	155	12
Kurtosis of Young modulus	$K(E)$	–	175	10

The values calculated for the test of the variance analysis according to the double classification are presented in ***Table 9***.

Analysis of the data shows that:

- the changes in the needle roller velocity V_F and draw ratio R_F do not have a significant influence on the tenacity W_t of the fibers,
- the changes in the needle roller velocity V_F statistically affect the value of the elongation at break ε_r and Young modulus E.

Step 6. Determination of the regress function and assessment of their significance

The regress functions were determined for the mechanical parameters measured in the function of the needle roller velocity V_F. For fibres produced at draw ratio R_F = 10 the supplementary characteristic profile in the form of a straight line was found only for an elongation at break ε_r ($\hat{\varepsilon}_r = 23.151 + 0.0096\ V_F$, $R_w^2 = 0.9404$, $R_w = 0.9697$, $F_{calc.} = 31.6$, $F_{crit.} = 18.5$, where: $\hat{\varepsilon}_r$ – the value of the regress function of the elongation at break of fibrillated fibres, R_w – the coefficient of the multiple correlation, $F_{calc.}$ – calculated value of F-Snedecor statistics, $F_{crit.}$ – critical values of F-Snedecor statistics determined for K and N-K-1 degrees of freedom at significance level - α = 0.05). For other parameters the supplementary characteristic profile in the form of a straight line was not found. For fibres formed at draw ratio R_F = 12 the supplementary characteristic profile in the form of a straight line was found only for Young modulus E ($\hat{E} = 4.9213 - 0.0092\ V_F$, $R_w^2 = 0.9196$, $R_w = 0.9590$, $F_{calc.} = 22.9$, and $F_{crit.} = 18{,}5$, where: $\hat{E}$ – the value of the regress function of the Young modulus of fibrillated fibres). For other parameters the supplementary characteristic profile in the form of a straight line was not found. The supplementary characteristic profile in the form of a parabola was not found for all parameters measured.

Step 7. Choosing of useful settings of the extruder technologically

Statistical parameters of the distribution of mechanical parameters of the fibrillated fibers analysed, which were selected from the choice of optimum variants, are presented in ***Table 10***.

Analyzing the data, one can conclude that the most beneficial combination of settings for the formation parameters is the combination V_F = 155 m/min and R_F = 12. The other possible combination which also deserves on attention is V_F = 175 m/min and R_F = 10.

Summary

On the basis of the analysis of literature of the subject and investigations conducted one can affirm that various ways of concrete reinforcement exist, one of which is using to armature classic or fibrillated polypropylene filaments. Unfortunately, classic filaments of PP possess small adhesiveness to the cement matrix and can be easily removed under the influence of mechanical strengths. It is now extremely essential to produce fibrillated PP filaments at well-chosen parameters of fibrillation. The investigations conducted showed that the most beneficial combination of settings for the formation parameters is V_F = 155 m/min and R_F = 12. Another possible combination which also deserves attention is V_F = 175 m/min and R_F = 10.

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