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Knitted Meshes for Reinforcing Building Composites

DOI: 10.5604/01.3001.0013.1826

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Abstract
Modern technical textiles, including knitted fabrics, are widely used in the construction industry. Regarding textiles in concrete reinforcement, methods based on shredded fibres, meshes, reinforcing mats, woven textiles and knitted DOS tapes are frequently used as underlays of concrete constructions. Textiles are also used in the reinforcement of fibrous FRP composites. The research presented focused on producing composites made of Mapei Mapefill concrete mass with reinforcement in the form of three variants of knitted meshes made of 228 tex polyamide threads, polypropylene threads of 6.3 tex and 203 tex glass threads, as well as identification of their mechanical properties. The mesh variant made of glass fibre is especially noteworthy, as its strength is more than three times higher than that of polyamide meshes. At the same time, a very small relative elongation of 3% is observed for this variant of knitted fabric, which is a desired property regarding the comparatively low stretching extension of concrete. In the process of making the composites, the adhesion of the concrete mass to the surface of the threads was analyzed. For this purpose, a "Sopro HE449" type agent was used. Composite beams were subjected to a three-point bending strength analysis on a testing machine. The results of strength measurements of the composites obtained prove that those with glass fibres demonstrate a threefold increase in strength compared to the original concrete beam.

Key words: *technical knitted fabrics, knitted composite reinforcements, knitting technology, reinforcing meshes, strength characteristics, knitted meshes, building composites, strength tests, composites.*

Introduction

Modern textile technologies frequently focus on technical textiles, including those used in the construction industry. Nowadays traditional strengthening of building structures is often replaced with modern textile reinforcements.

The first studies and patents concerning composites for construction in the form of reinforced concrete structures appeared in France at the beginning of the second half of the 19th century [1]. In Poland, Hennebique systems were introduced on an industrial scale by the company "J. Sosnowski and A. Zacharewicz", which before the First World War constructed many reinforced structures for civil engineering and over 200 reinforced concrete bridges.

The development of man-made and synthetic fibre technologies in the 1960s and 1970s (carbon fibres 1961, aramid fibres 1972) created opportunities for an alternative reinforcement of building structures, including concrete, with modern textile materials.

The term "Tekbet" appeared, which stands for a composite made of concrete reinforced with textile structures (Textil Reinforced Concrete – TRC) [2]. A significant modification of concrete properties can be achieved by introducing a fibre additive in the form of fibres dispersed in a concrete mix. The idea of using fibres as reinforcement was developed by W. Bobeth [3], while the systematics of oriented fibres were provided by M. Curback [4].

Concrete with structural reinforcement (fibro-concrete) belongs to the group of special concretes [5] and has better properties compared to ordinary concrete, including high resistance to crack formation, good fatigue and impact resistance, and often higher tensile and shear strength [6-8]. Reinforcing concrete with fibres has been used in widely understood practice since the 1960s. In the reinforcement of concrete, textile materials are also applied in the form of meshes, most often obtained using knitting technologies.

The next issue in the reinforcement of concrete structures is the use of FRP fibrous composites (Fiber Reinforced Polymers), which can be divided into two groups: materials for construction reinforcement and bars of reinforcing concrete. The first non-metallic reinforcing bars appeared on the market in the early 1990s [10, 11]. The fatigue strength of the FRP composite is much higher than the fatigue resistance of metals. In Poland, such products as a replacement for traditional steel reinforcements are not yet widely used in modern building technologies. An important group of textiles applied in the construction industry are, among others, geomaterials.

This publication presents a selected case of a building composite reinforced with "pure" knitted meshes, made using the technology of warp knitted fabrics. Analysis of the bending strength of model beams was performed for three variants of reinforcement. The aim of the research conducted was to formulate guidelines for the technological design of concrete reinforcement with textile meshes.

Research program and material

The research program focused on the development of stitches for warp knitted structures of openwork meshes used to reinforce concrete, together with strength analysis of the components of the building composite and study of the influence of warp and reinforcement properties and the connection technology on the static strength of this composite.

Characteristics of the warp – concrete mortar

The product called Mapefill, made by the global company Mapei, was selected for the tests. This product is non-shrinkage concrete mortar with high liquidity for anchoring and casting.

Mapefill is a powdered premixed mortar consisting of high-strength cement, aggregates and special additives containing contraction compensating substances. Due to the presence of specific additives, the Mapefill product shows neither plastic contraction (ASTM 827 standard) nor contraction in the hardening phase (UNI 8147 standard), which results in very high compressiveand bending strength obtained in a short time (***Table 1***).

Characteristics of the reinforcement

The textile reinforcement used in the composite is a knitted structure in the form of a mesh (warp knitted fabric). The reinforcement stitch is made of two and three component stitches. There are connections with closed and open loops of tricot stitch and open atlas stitches n = 4, as well as a marquisette of rectangular a-jours reinforced with weft threads. The stitches were designed in ProCad warpknit software. Knitted polyamide meshes Pa6 variants 1 and 2 have a very similar structure, differing only in the size of the course repeat. These differences result in different shapes and sizes of the mesh openings.

Table 1. *Safety data sheet of Mapefill [12].* ***Note:*** *(*)The sample was made in accordance with EN 1881, for an even distribution of tensions between reinforcing bars and Mapefill.*

„MAPEFILL": TECHNICAL DATA (typical values)			
1. PRODUCT PROPERTIES			
Type:		CC	
Maximum grain size of aggregate:		2.5 mm	
2. UTILITY PARAMETERS (relative humidity in +23° C – 50%)			
Operating temperature range:		from +5 °C to +35 °C	
Smoothness after mixing (EN 13395-2):		>45 cm	
Mixing ratio with water:		100 parts of Mapefill with 14÷15 parts of water (3.50-3.75 l of water for each 25 kg sack)	
Bulk density:		2150-2350 kg/m³	
PH of the mixture:		>12.5	
Maintaining working properties:		about 1 hour	
3. FINAL PROPERTIES (14.5% of water to mortar)			
Compressive strength:	EN 12190	>80% of the value declared by the manufacturer	>30 MPa (after 1 day) >55 MPa (after 7 days) >70 MPa (after 28 days)
Bending strength:	EN 196/1	not required	>5 MPa (after 1 day) >8 MPa (after 7 days) >9 MPa (after 28 days)
Elasticity modulus under compression:	EN 13412	not required	27 GPa (after 28 days)
Adhesion to concrete (MC 0.40- relation w/c = 0.40) according to EN 1766:	EN 1542	not required	≥2 MPa (after 28 days)
Adhesion at pulling out steel bars – displacement under load of 75 kN	EN 1881	<0.6mm	<0.1mm
Expansion in plastic state:	ASTM 827	not required	≥0.3 %
Adhesion of anchored reinforcing bars made of Mapefill	EN 1881 (*)	not required	> 25 MPa

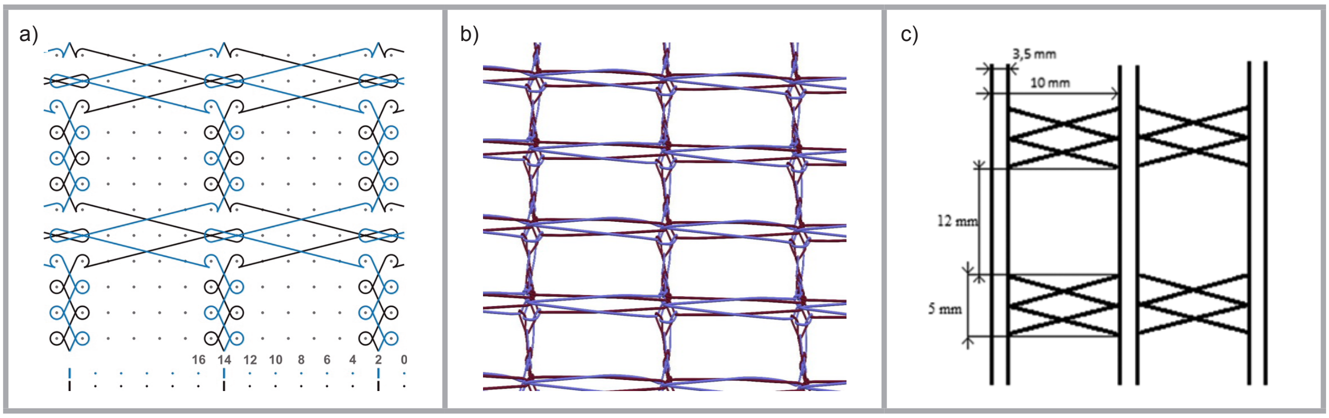

Figure 1. *Stitches of reinforcement made of knitted mesh variant Pa6_1: a) schematic drawing of a stitch on the needles, b) drawing of stitches showing a real arrangement of yarn using the ProCad warpknit software environment, c) model diagram of a truss built of vertical wales and horizontal courses (actual mesh dimensions).*

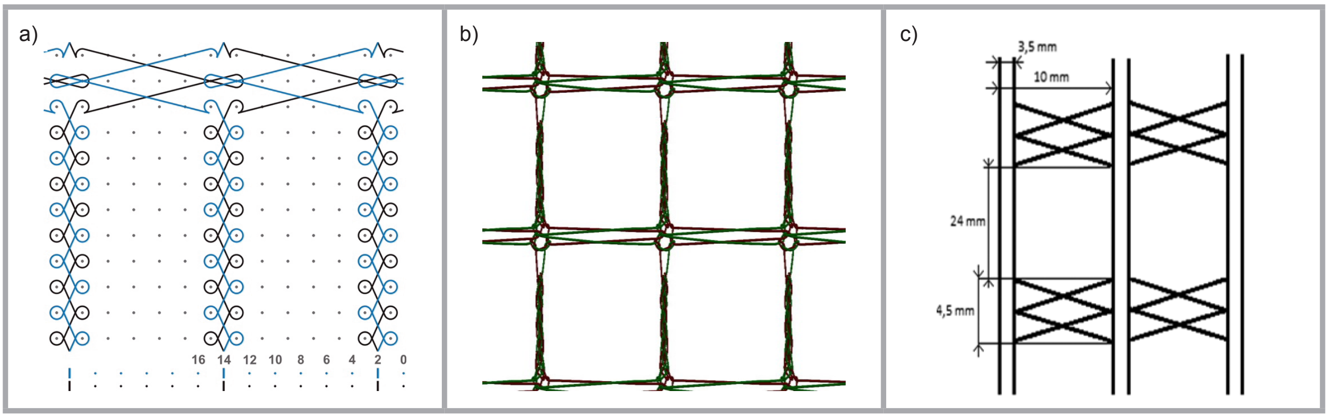

Figure 2. *Stitches of reinforcement made of knitted mesh variant Pa6_2: a) schematic drawing of a component stitch of the mesh, b) drawings of stitches showing real arrangement of yarn using the ProCad warpknit software environment, c) model diagram of a truss built of vertical wales and horizontal courses (actual mesh dimensions).*

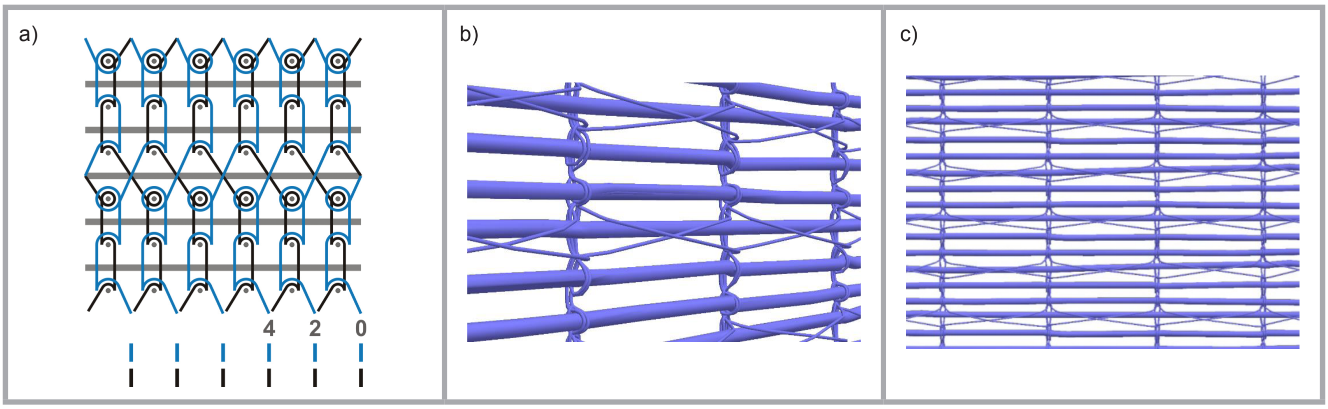

__Figure 3.__ Stitches of reinforcement made of knitted mesh variant PP+FG: a) schematic drawing of a component stitch of the mesh, b) and c) drawings of stitches showing real arrangement of yarn using the ProCad warpknit software environment.

Design of knitted meshes

a) Warp knitted fabric: variant 1, Pa6_1
A knitted mesh made of double twisted polyamide threads with wale repeat R_w = 6 wales and course repeat R_c = 6 courses. Thread characteristics together with their strength properties are presented further in the publication (***Figure 1***).

b) Warp knitted fabric: variant 2, Pa6_2
A knitted mesh made of double twisted polyamide threads with wale repeat R_w = 6 wales and course repeat R_c = 6 courses (***Figure 2***).

c) Warp knitted fabric: variant – PP+FG
The knitted fabric stitch consists of three component stitches. Two symmetrical stitches with pillar and tricot laps form the basic fabric, a so-called marquisette of rectangular a-jours, into which weft threads of the third component stitch made of fibreglass are horizontally interlaced.

The marquisette a-jours were made of thin PP threads with a linear density of 6.3 tex, while the weft threads were made of fibreglass with a significant linear density of 303 tex (***Figure 3***).

Characteristics of the threads

Thread strengths and linear densities were determined according to the following standard: PN-EN ISO 2062:2010. "Textiles – Yarns from packages – Determination of single-end breaking force and elongation at break using constant rate of extension (CRE) tester". The strength tests were carried out on a Hounsfield tensile tester type H50KS England (thread length between the clamps – 500 mm, tensile speed – 200 mm/min). The results obtained are presented in ***Table 2***.

__Table 2.__ Summary table of linear densities and strength parameters of threads.

No.	Thread type	Real linear density, tex	Breaking force, N	Relative elongation, %	Elongation Δl, mm	Specific strength, N/tex	Young's modulus, GPa
1	Polyamide 6 (Pa6)	228.1	53.2	12.6	63.1	0.233	2.19
2	Polypropylene (PP)	6.3	2.0	18.1	83.2	0.322	1.70
3	Fibreglass (FG)	303.0	83.3	1.3	6.4	0.275	55.01

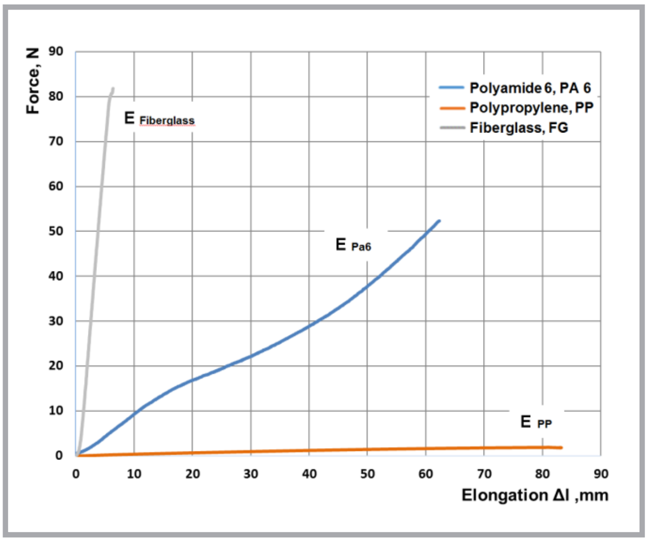

__Figure 4.__ Strength characteristics of threads.

Discussion of test results regarding thread properties

Absolute values of the breaking forces were analysed for threads with different linear densities transferring the loads. The greatest value of the force was observed for threads made of fibreglass, whose average strength was 83.3 N. The polypropylene threads applied were characterised by a small linear density of 6.3 tex and strength of 2.3 N. These threads in the composite structure do not carry tensile loads. Polyamide threads with a linear density of 228 tex were characterised by a breaking force of about 53.2 N. The best absolute values of tensile forces determining strength properties of the composite were observed for threads made of fibreglass.

Analysis of the specific (relative) strength with respect to the linear density shows that the raw materials used to limit the extensibility of the concrete structure have very similar properties (glass fibre 0.28 N/tex, polyamide 0.23 N/tex).

This suggests that threads with the same linear densities would have similar strength properties. An interesting phenomenon was the polypropylene thread, characterised by the highest relative strength.

If polypropylene threads used for reinforcement possessed the same linear density as polyamide or fibreglass threads, then they would be characterised by the highest value of absolute strength.

When assessing threads for composites, elongation is a very important property as it has a significant impact on the strength properties of building composites subjected to the bending process. A fibreglass thread is characterised by very low relative elongation, which is a positive property in the context of the composites analysed. A low deformation value with a significantly high tensile force makes it possible to claim that a knitted mesh with fibreglass will be the most advantageous (optimum) variant of concrete reinforcement.

Considering the inclination angle of curves of force dependence as a function of elongation, it can be concluded that the elasticity modulus for glass threads is much higher than for polyamide threads and slightly higher than for polypropylene threads.

$$E_{\text{FIBREGLASS}} >> E_{\text{Pa6}} > E_{\text{PP}}$$

Technology of knitted reinforcing meshes

The knitted structures designed were made on a Karl Mayer raschel machine RL5NF, with needle gauge E12. The threading of both needle combs was compatible with the 1/5 threading repeat, and the threaded guide bars were arranged opposite each other.

In the third variant, a fibreglass thread was additionally introduced in the form of a horizontally arranged roving. Due to the lack of appropriate additional devices on the knitting machine, the horizontal weft was introduced manually.

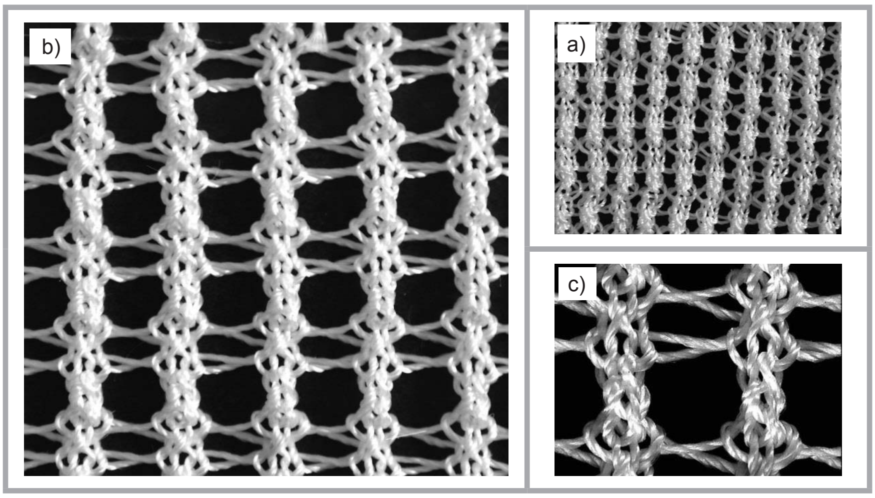

Figure 5. *Polyamide 6 knitted fabric; variant Pa6_1 in a relaxed state and in the tension phase.*

Characteristics of the knitted fabrics produced

*a) Warp knitted fabric: variant 1. Pa6_1 made of polyamide 6 (**Figure 5**).*

Fabric thickness: 2.50 mm.
Pattern chain notation:

guide bar 1:	2,2,0,0/2,2,4,4/2,2,0,0/2,2,4,8/12, 14,16,12/8,4,2,2//
guide bar 2:	14,14,16,16/14,14,12,12/14,14, 16,16/14,14,12,8/6,2,0,6/8,12, 14,14//

*b) Warp knitted fabric: variant 2. Pa6_2 made of polyamide 6 (**Figure 6**).*

Fabric thickness: 2.46 mm.
Pattern chain notation:

guide bar 1:	2,2,00/2,2,4,4/2,2,0,0/2,2,4,4/2, 2,0,0/2,2,4,4/2,2,0,0/2,2,4,4/2,2, 0,0/2,2,4,8/ 12,14,16,12/8,4,2,2//
guide bar 2:	14,14,16,16/14,14,12,12/14,14, 16,16/14,14,12,12/14,14,16, 16/14,14,12,12/14,14,16,16/14, 14,12,12/14,14,16,16/14,14,12, 8/6,2,0,6/8,12,14,14//

*c) Warp knitted fabric: variant 3. PP,FG made of polypropylene and fibreglass in the form of roving (**Figure 7**).*

Fabric thickness: 0.84 mm.

Pattern chain notation:

guide bar 1:	2,2,4,4/4,4,2,2/2,2,4,4/4,2,0,0/0, 0,2,2/2,2,0,0//
guide bar 2:	2,2,0,0/0,0,2,2/2,2,0,0/2,2,4,4/4, 4,2,2/2,2,4,4//

The above photographs of the knitted fabrics present: the knitwear with the real arrangement of threads (***Figure 5.a, 6.a, 7.a***), knitted fabric stretched along the course and wale structure of the fabric embedded in the concrete mass (***Figure 5.b, 6.b, 7.b***), and an enlargement showing the knots connecting adjacent wales (***Figure 5c, 6c, 7c***).

For the three types of knitted fabrics, strength measurements were made on a Hounsfield machine type H50KS according to Standard PN-EN ISO 13934-1: 2002.

The tests were made for each variant of knitwear, which was stretched along both the courses and wales. The distance between the jammed jaws was 200 mm. The stretching speed for the fabrics analysed was 100 mm/min. The results obtained from the tests are presented below in ***Table 3*** and in the chart – ***Figure 8***.

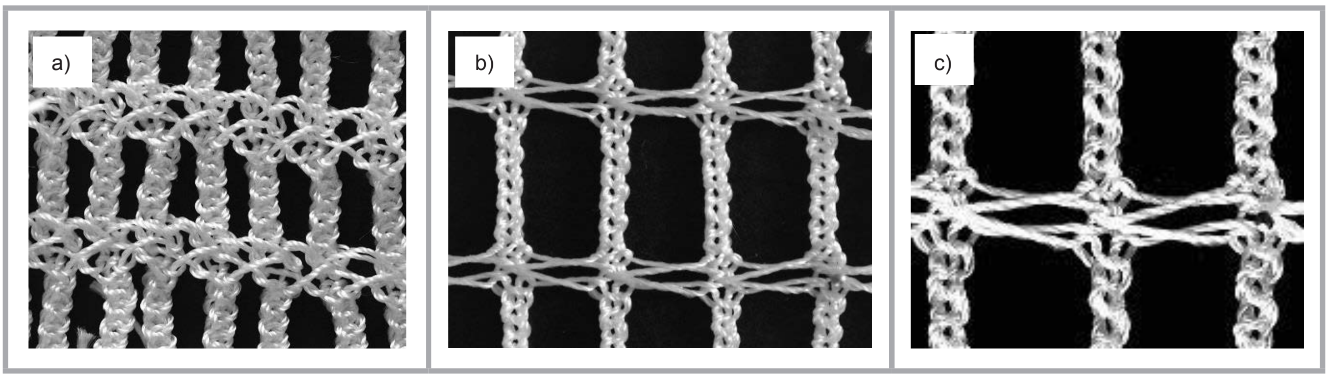

Figure 6. *Polyamide 6 knitted fabric; variant Pa6_1 in a relaxed state and in the tension phase.*

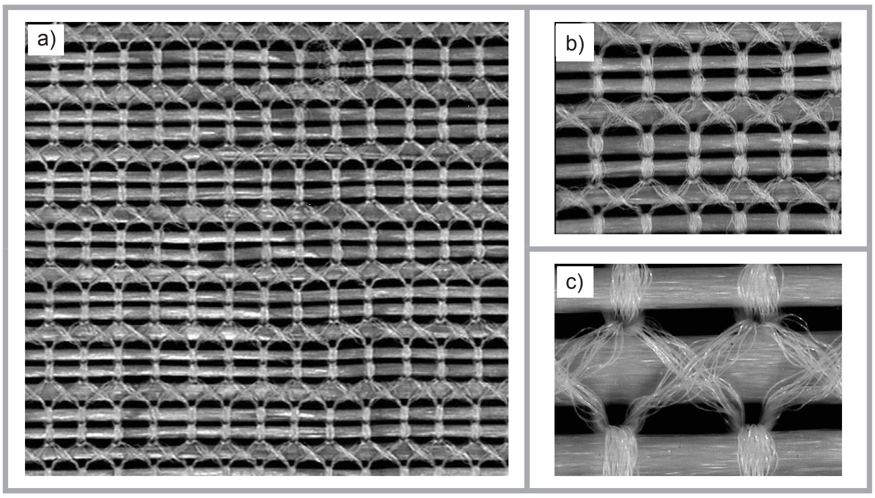

Figure 7. Knitted fabric made from polypropylene and fibreglass; variant PP, FG in the tension phase and in a relaxed state.

Analysing the results above from ***Table 3*** together with the graphs – ***Figure 8***, it can be noticed that in the case of polyamide knitted meshes, the maximum breaking forces along the wales are larger than those along the courses. In variant 1, the breaking force is 2.4 times higher, and in the case of variant 2-1.9 times higher. In variant 3, the opposite takes place, as thanks to the inserted horizontal wefts made from fibreglass, the breaking forces along the courses are fourteen times higher than those along the wales. There are also some differences in elongation, both in the direction along the courses and wales. Polyamide meshes possess much larger elongations than those made from polypropylene and glass threads. The above-mentioned parameters of the knitted fabric suggest an optimum arrangement of the reinforcement structure. In order to improve the properties of the composite, the reinforcement should be arranged along the stretching line for greater strength, in the first two cases – along the wales in the direction of the tensile forces acting in the composite, and in the third case – along the courses.

Table 3. Strength parameters of knitted meshes.

Mesh type	No.	Breaking force along wales, N	Elongation along wales, %	Breaking force along courses, N	Elongation along courses, %
Pa6_1	1	1180	127.1	473.5	175
Pa6_2	2	962	109.6	485	163
PP, FG	3	217.5	47.33	3204	5.50

Taking into account the significant elongation of polyamide meshes occuring along the wales (in the direction of reinforcement), the meshes in the mould were pre-stretched to a size of relative elongation equal to ε = 20%, before pouring the reinforcement with mortar, (i.e. Δl = 40 mm, diagrams: ***Figure 8***).

Building the composite

The composite was made in plastic moulds with a rectangular shape by combining Mapefill building material and reinforcement in the form of a warp knitted mesh.

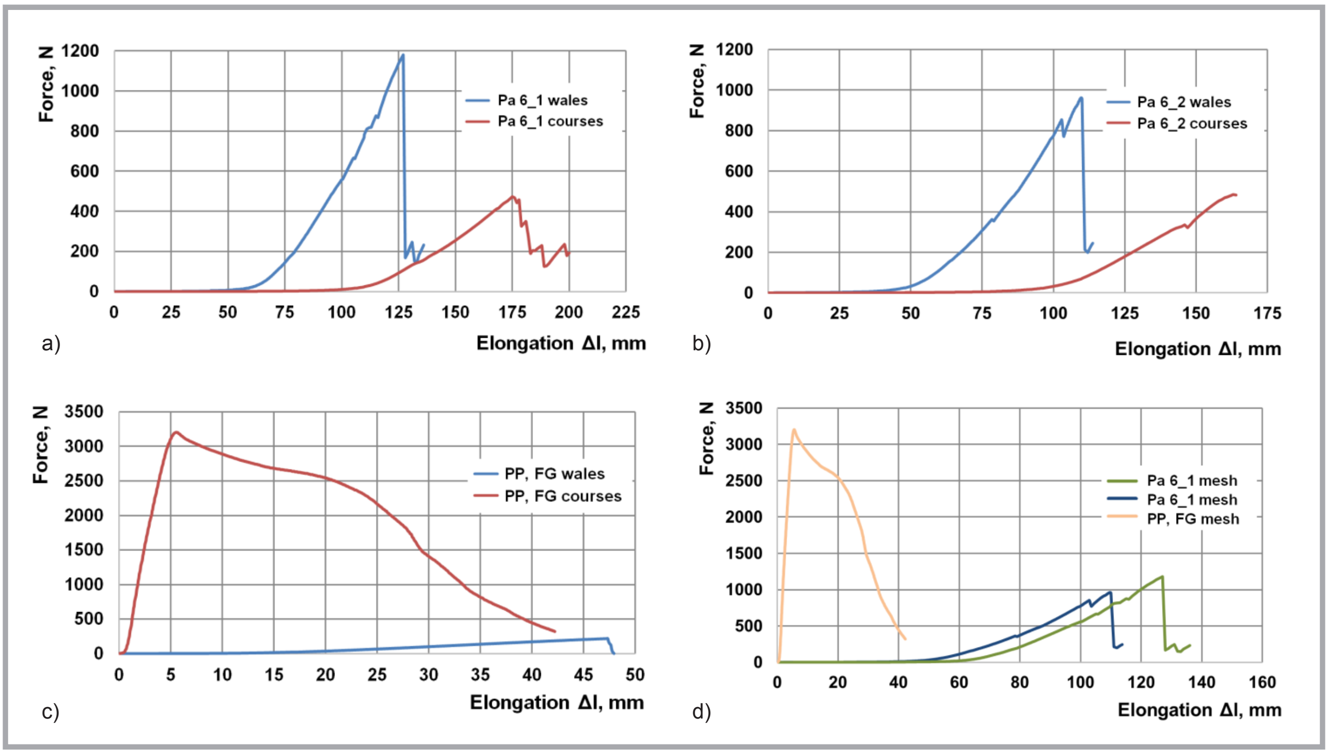

Figure 8. Strength characteristics of knitted meshes: a) diagram of stretching polyamide thread; variant: 1 – Pa6_1, b) diagram of stretching polyamide thread; variant: 2 – Pa6_2, c) diagram of stretching polypropylene mesh with fibreglass roving; variant: 3 – PP, FG, d) summary diagram of strength characteristics of tested knitted meshes along the direction of reinforcement.

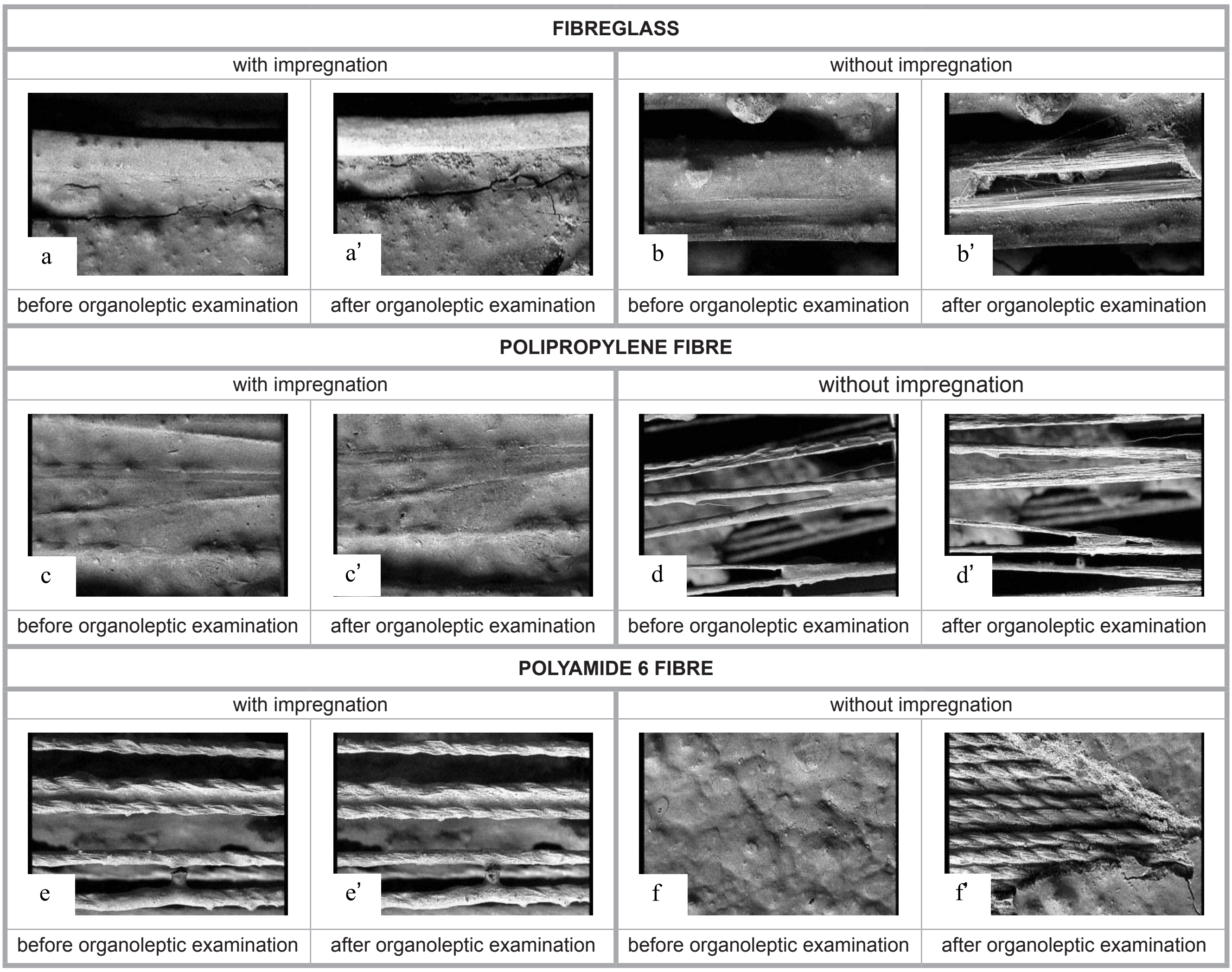

Figure 9. *Photographs of thread surfaces with and without impregnation, covered with concrete mass.*

The height of the textile reinforcement was established in relation to the bottom layer of the composite at 5 mm, which resulted from literature data in the study of Janusz Pędziwiatr "Introduction to the design of reinforced concrete structures..." [13]. Calculation standards and procedures for determining the location of the reinforcement in the composite are presented in literature [14, 15]. 50 mm wide beams were cut out from a ready-made composite block 30 × 200 ×350 mm, and then subjected to three-point bending.

Composite manufacturing technology

An important element in the manufacturing technology of a composite consisting of two different materials is the adhesion of one component to the other. Adhesion is especially important for the proper connection of threads strengthening the knitted structure with the second component, which is concrete mass. For this reason, one of the first stages before the actual composite was produced was testing the impact of thread impregnating agents on the strength of the connection between the textile material and the binder. The Mapei impregnant "Sopro HE449" was used for the tests. Samples were prepared in the form of six frames wrapped with the fibres selected for the study, with two frames for each type of fibre.

The frames were divided into two groups: every second was covered with the impregnating agent, and then all of them with a layer of concrete mortar, which were then left for a period of about one week, after which the adhesion of the mortar to the surface of the fibres was examined by the organoleptic method. The degree of adhesion of the concrete mass to the threads was observed during mechanical friction. The organoleptic tests showed that the adhesion of concrete was significantly higher in the case of impregnated samples, as confirmed by the photographs in ***Figure 9***.

Photographs of threads covered with concrete mortar

Photographs of the test samples of **fibreglass** covered by concrete with impregnation – variant (a) and without impregnation – variant (b), photographs of samples of **polypropylene fibres** covered by concrete with impregnation – variant (c) and without impregnation – variant (d), photographs of samples of **polyamide fibres 6** covered by concrete with impregnation – variant (e) and without impregnation – variant (f).

Looking at the photographs above, it can be noticed that figures a) and a') do not differ significantly. The variant with impregnation had not changed after the test, in contrast to variant b), where in the case of sample b') some concrete mass had been removed from the threads.

In the case of variant c) with impregnation, small changes were visible after the organoleptic examination, which means

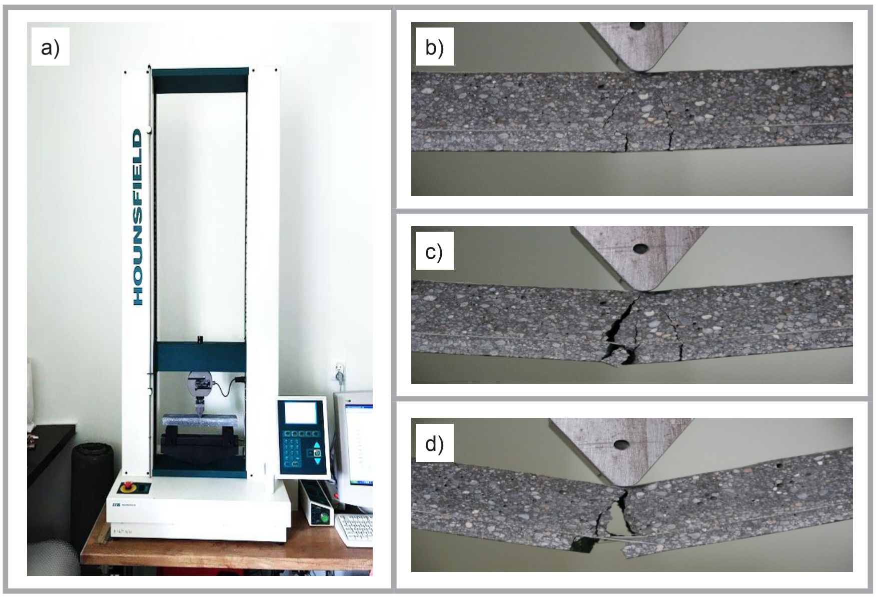

Figure 10. *Bending strength tests of concrete composites: a) three-point attachment of concrete samples; photographs of concrete composite with polypropylene mesh and fibreglass roving, b) initial stretching phase, c) middle stretching phase, d) final stretching phase.*

that the concrete adheres to the threads, while in the case of variant d') concrete had been almost completely removed from the surface of the threads.

Comparing the photographs of test samples of variant e) with impregnation obtained, it can be seen that the differences are negligible. However, variant f') without impregnation had changed significantly, which indicates poor adhesion of concrete to the fibre surface.

The research presented shows that better results of connecting concrete mass with the thread structure are obtained by pre-impregnating the thread material.

Composite production process

In the first part of the process, warp knitted meshes were produced whose task was to strengthen the composite.

The threads were impregnated in order to improve their adhesion to concrete. Then concrete mortar was mixed with water in appropriate proportions, in a manner recommended by the manufacturer, and with the help of additional tools, and then it was placed in 300 cm × 250 mm moulds. The next step was placing the knitted reinforcements with a particular stretching ratio at a distance of 5 mm from the bottom layer of the composite, after which the mixture was poured with concrete again in order to cover the entire mould. The total period of concrete curing lasted 21 days, after which time, the composite blocks obtained, with overall dimensions of 300 cm × 250 mm, were cut into beams 50 mm wide, 30 mm high and 300 mm long. The samples cut were used for strength analysis in the bending process.

Strength test of the composite

Bending of the composite beams was carried out on a Hounsfield device, type H50KS. A handle equipped with a head with a bearing capacity of 50 kN and width of 50 mm was specially prepared for the device. The bending test was carried out at a speed of 0.6 mm/min. The 300mm long beams were placed on the grips, spaced at a distance of 200 mm (***Figure 10.a***).

In the initial phase of bending, the first cracks could be observed on the concrete structure (***Figure 10.b***). In the case of "pure" concrete without reinforcement, the sample was completely damaged. When using a composite, for the same deflection values, the beam was also damaged, but not completely. The structure of the beam was maintained due to the reinforcement. Even in the case of significant damage, the composite element was not completely disintegrated, due to the presence of textile reinforcement threads placed in the lower layer of the concrete mass, which keep the structure together (***Figures 10.c*** and ***10.d***).

From a mechanical point of view, the beam was damaged when pressure was first exerted on the sample; but although the structure cracked, it did not disintegrate thanks to the use of the reinforcement.

Figure 11 presents a set of diagrams showing strength characteristics of the composite beams subjected to bending.

The sample made of pure concrete is a reference point for all the other samples, thanks to which it is possible to assess whether the reinforcement fulfilled its task. From the diagram (***Figure 11***), it can be seen that the sample made of pure concrete without any reinforcement has a strength of 1089 N and deflection of 0.8 mm. The variant reinforced with a knitted mesh made of fibreglass exhibits a maximum strength of 2128 N. The diagram shows that the strength

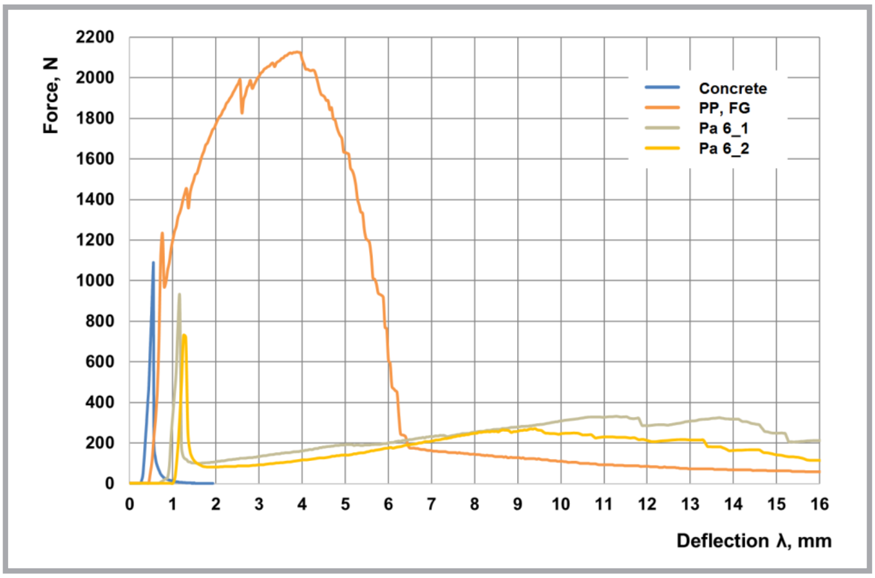

Figure 11. *Summary of strength characteristics of composites tested.*

characteristics of this composite has five peaks, which represent microcracks in the concrete structure. Despite further damage to the sample, the values of the compression and stretching force increase, due to the reinforcement embedded in the concrete beam. Due to the compact structure of the fibreglass mesh and high value of Young's elasticity modulus characterising the threads of which the fabric was made.

E = 55.01 GPa, the strength of the composite exceeds that of pure concrete. In the case of the other two variants of reinforcements made of polyamide knitted meshes, their strength is lower than that of the variant without any reinforcement. In the first variant, the cracking force is 918 N and in the second – 732 N, probably due to the fact that the knitted meshes placed in the concrete layer were not stretched properly.

Elasticity analysis of component materials and building composites

For a comparative assessment of strength properties of the composites reinforced with knitted meshes tested, longitudinal elasticity moduli were determined for the textile materials and for the composites. The calculation methodology and results of Young's elasticity moduli are presented below.

Young's elasticity modulus for threads

The phenomenon of elastic strain was defined by Hooke's law, which states that the "elastic strain of the body is proportional to the force that is applied to it" [16]. The law applies to any configuration of forces and body shape, and is determined by the relationship represented by the ***Equation (1)***:

$$\Delta l = \frac{F*l}{E*S} \qquad (1),$$

where: F – breaking force, N; l – yarn length, mm; E – material constant– Young's modulus, Pa; Δl – ultimate elongation, mm; S – cross-section of the thread, m^2.

Adopting a circular cross-section of the thread, the surface S is determined according to the following ***Equation (2)***:

$$S = \pi r^2 = \pi * (\frac{d}{2})^2 = (\frac{\pi}{4}) * d^2 \qquad (2),$$

where: d – minimum thread thickness, m^2.

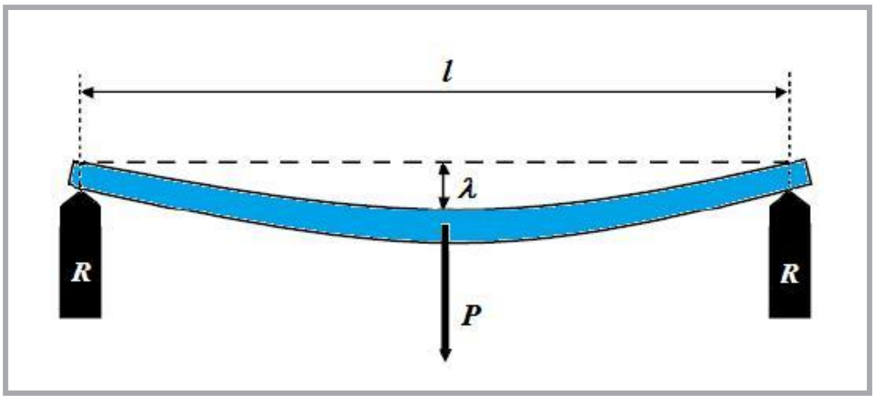

Figure 12. *Deflection of a supported „bar" at both sides using force P.*

Two thicknesses of the threads can be distinguished in the fabric structure: thread thickness in a relaxed state, including free spaces, and in the tension phase, for a compact structure. The thickness of the stretched thread, otherwise known as the minimum thickness, was used for the tests, calculated from the following ***Equation (3)***:

$$d = \sqrt{\frac{T_t}{785*\rho_t}} \qquad (3),$$

where: d – minimum thread thickness, *mm*; ρ_t – specific weight of the fibre material, $\frac{g}{cm^3}$; T_t – thread linear density, tex; $\frac{g}{km}$.

Young's modulus for reinforcing fabrics

1) Elasticity modulus E for knitted fabrics made of glass threads

In one centimeter of the knitted fabric there are 9 threads made of fibreglass; hence in the sample tested with a width of 5 cm there are 45 fibreglass threads. Young's modulus was calculated from the ***Equation (4)***:

$$E = \frac{F*l}{Ssum*\Delta l}, \frac{N}{m^2}, \qquad (4)$$

where: S_{sum} – total cross-section, m^2;

S_{sum} = 0.00000524 m^2; E = **11.125 GPa**

2) Elasticity modulus E for knitted fabrics made of polyamide threads

In the 5 cm test sample there are 5 wales consisting of 6 threads. As the two samples of meshes prepared were made from the same raw material and had different sizes but the same number of wales and threads in the width of the sample, the average value of the strength and average elongation were used for the calculations.

S_{sum} = 0.000005886 m^2; E = 0.154 GPa

Average values used for the calculations: average bending force,

$$F = \frac{962+1180}{2} = 1071 \text{ N},$$

elongation,

$$\Delta l = \frac{127,1+109,6}{2} = 118.35 \text{ mm}.$$

Young's modulus for composites

One of the methods for measuring the elasticity modulus for thick elements such as bars is that of deflecting the "bar" supported on both sides. Under the influence of the force perpendicular to the bar P and that applied in its middle part, a deflection occurs.

Deformation of opposite body surfaces in the form of simultaneous compression of the upper surface and stretching of the bottom surface is also observed, while the middle part remains neutral, and not affected by any forces. Stretching and compression occur within the limits of elastic strain, in relation to which Hooke's law can be applied, where the unit of deformation is λ – deflection. This method allows to determine Young's modulus E using the relationship from ***Equation (5)***, bearing in mind that this relationship refers to bodies with a rectangular cross-section:

$$E = \frac{P*l^3}{4*\lambda*a*b^3}, \frac{N}{m^2}, \qquad (5),$$

where: P – beam bending force, N; l – beam length between the supports, mm; E – material constant – Young's modulus, Pa; λ – deflection, m; a – width of rectangular beam, m; b – height of rectangular beam, m.

Discussion of Young's moduli test results

A summary of test results is presented in ***Tables 4-5***.

Table 4. *Summary of results concerning parameters of knitted meshes.*

Variants of knitted meshes	Breaking force	Ultimate elongation	Young's modulus E
Polyamide 6_1 (grid)	1180 N	Δl = 126 mm	0.154 GPa
	Along wales, 30 threads	Ɛ = 63%	
Polyamide 6_2 (rectangle)	962 N	Δl = 109 mm	
	Along wales, 30 threads	Ɛ = 54.5%	
Fibreglass	3204 N	Δl = 6.0 mm	11.13 GPa
	Along courses, 45 threads	Ɛ = 3%	

Table 5. *Summary of results concerning parameters of building composites.*

Composite	Bending force	Deflection λ, Elongation of bottom layer of composite Δl	Young's modulus E
Concrete mortar	1089N	λ = 0.6 mm	2.69 GPa
		Δl = 0.0036 mm	
Polyamide 6_1 (grid)	918 N	λ = 1.0 mm	1.36 GPa
	Along wales, 30 threads	Δl = 0.005 mm	
Polyamide 6_2 (rectangle)	732 N	λ = 1.4 mm	0.78 GPa
	Along wales, 30 threads	Δl = 0.0077 mm	
Fibreglass	2128 N	λ = 1.59 mm	0.79 GPa
	Along courses, 45 threads	Δl = 0.127 mm	

Discussion of research results concerning the properties of knitted meshes

Comparing the mechanical properties of the knitted meshes, it can be seen that the values are different depending on the type of raw material from which the meshes were made and the directions towards which they were stretched. Polyamide meshes demonstrated almost more than twice higher maximum breaking forces along the wales than along the courses. Unlike in the case of polypropylene mesh, thanks to the introduction of horizontal wefts made of fibreglass, the breaking force along the courses was fourteen times higher than along the wales.

Polyamide meshes have much higher elongation values than those made of fibreglass and polypropylene (variant Pa6_1). The knitted meshes obtained demonstrate the same tendencies as the threads from which they were made. This rule applies to the elongation value, breaking force as well as parameters such as deformability, which is connected with Young's modulus.

Polyamide threads, just like the meshes made of them, have a much lower E value than fibreglass. The low level of deformability is a positive property in the case of reinforced composites; therefore, fibreglass mesh is the optimum variant.

Determination of the properties above was necessary to define the optimum arrangement of the reinforcement in the composite, which determines the composite strength during stretching.

Discussion of research results concerning composite properties

The highest value of the bending force – 2128 N, accompanied by small deflection, was observed for the composite with fibreglass reinforcement. Composites with polyamide reinforcement (bending forces: 918N and 732N), irrespective of their structure, have much lower strength than the concrete itself, whose destructive bending force equals 1089N. The relationships above indicate that the reinforcement in the form of polyamide mesh deteriorated strength properties of the composite, which was a bit disappointing because the initial thesis assumed that composites reinforced with knitted meshes would demonstrate better strength parameters. Such unfavorable values in the case of composites with polyamide meshes result from the thread parameters, the structure of the knitted fabric and too small initial elongation of the reinforcing mesh in the process of composite formation.

Pre-stretching of the mesh before it is embedded in the concrete mortar would eliminate this unwanted extensibility and straighten the wales. The reinforcement structure would also change its volume, which would facilitate the process of connecting the fibre structure to the concrete mass.

In the strength characteristics of the composite with fibreglass, several peaks can be observed, indicating micro-cracks in the composite structure, while the value of the bending force still increases. This results from damage to the concrete structure and cooperation with the fibre glass reinforcement.

Summarising the research results, it should be emphasised that when designing composite structures, the properties of raw materials used for reinforcements should be taken into account. By examining the thread, it is possible to predict the properties of the reinforcing mesh and the behaviour of the composites. Raw materials used for reinforcements should be characterised by the highest possible strength and smallest elongation Δl, similar to that of pure concrete. Compatibility between the elongation and high strength of the reinforcement guarantees high functional parameters of the composite.

Summary and conclusions

- Results of the literature study on textile reinforcements in building composites indicate that textiles, including knitted fabrics, are widely used in the construction industry in areas such as road structures and surfaces, the engineering of bridges and viaducts, river and sea fortifications, building constructions, and specialised industrial and military infrastructures.
  Various methods are used for reinforcing concrete with textile structures, including shredded fibres, meshes, reinforcing mats, woven textile and knitted DOS tapes used as the underlay of concrete constructions, as well as FRP fibrous composites.
- The research programme presented focused on producing composites made from Mapei Mapefill concrete mass with reinforcement in the form of knitted meshes, and identification of their mechanical properties. The concrete mass was characterised by a high compressive strength – above 70 MPa, and a significant bending strength – above 8 MPa (elasticity modulus under compression 27 GPa). The mass was professionally prepared to form a composite. Three variants of knitted technical meshes made of polyamide, polypropylene and fibreglass threads were used as reinforcement.
- Three variants of warp knitted fabrics were designed using the ProCad warpknit software environment. Two

variants were in the form of rectangular meshes, differing in the openwork area, and one variant had horizontal weft threads made of fibreglass.

The three variants of mesh reinforcements were made using the technology of multi-needle warp knitted fabrics on an RL5NF Karl Mayer warp knitting machine with needle gauge E12.

The fibreglass threads had a significant value of E moduli – 55.01 GPa, compared to polypropylene and polyamide threads, for which the moduli equaled 1.79 GPa and 2.17 GPa.

- The stitch structure of the knitted fabrics for composite reinforcement was subjected to microscopic analysis, and strength parameters of these fabrics were measured along the wales and courses.

Especially noteworthy is the variant of fibreglass mesh whose strength is more than twice higher comparing to that of polyamide meshes. At the same time, this variant of knitted fabric has a very low relative elongation of 3%, which is a positive property, comparing to the low stretching extension of the concrete mass.

The good strength properties of meshes made from fibreglass and their low elongation make them especially useful for composite reinforcement.

In the process of making composites, the adhesion of the concrete mass to the surface of the threads was also analysed. For this purpose, a "Sopro HE449" type agent was used – an emulsion improving concrete adhesion to reinforcing meshes.

- For the purposes of this research work, a technology of manually manufacturing a construction composite was developed, which was made from Mapei concrete mortar and the knitted mesh produced, spaced 5mm from the bottom layer of the composite.

Composite beams were subjected to strength analysis for three-point bending on a Hounsfield tensile testing machine type H50KS, where the speed of transverse deformation was 0.6 mm/min.

The results of strength measurements obtained showed that in case of the composite with fibreglass, strength properties were twice better compared to the original concrete beam.

- The research on reinforcements made from polyamide meshes, which weakened the concrete structure, was unsuccessful. The effect of the destructive impact of the reinforcement on strength properties of the composites can be ascribed to the absence of pre-stretching at a level above 20% in the composite production phase, as well as to the overly- extensive spatial structure of the mesh.

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Received 19.11.2018 Reviewed 29.04.2019