Manar Y. Abd El-Aziz, Z. M. Abdel-Megied, K. M. Seddik
Clothing and Knitting Industrial Research Department, Textile Research and Technology Institute, National Research Centre, 33 El Buhouth St, Ad Doqi, Dokki, Cairo 12622, Egypt

Enhancement Reinforcing Concrete Beams Using Polypropylene Cord-Knitted Bars

Izboljšanje ojačitve betonskih nosilcev s pletenimi kompozitnimi palicami iz polipropilenskih vrvic

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 12-2022 • Accepted/*Sprejeto* 4-2023

Corresponding author/*Korespondenčni avtor:*
Dr. Manar Yahia
Email: manar_yahia@hotmail.com
ORCID ID: 0000-0002-8254-8277

Abstract

Currently, technical fabrics play a major role in many industries due to their multiple characteristics. The aim of this research was to utilize composite knitted bars to reinforce concrete beams. Six cord-knitted samples with two different polypropylene yarn counts (outer layer) and three different core materials were manufactured and immersed in a local epoxy material (Kemapoxy 150). Composite knitted bars were prepared in this way. Several tests were conducted for fabrics and knitted bar samples. All data were collected and analysed using two different tools: ANOVA test and radar chart area. Finally, three concrete beams with a varying number of cord-knitted bars (one bar, two bars and three bars) were produced. The results indicated that the differences in outer and core yarns for cord-knitted samples have a significant effect on several fabric and bar characteristics. The knitted bars with PP core yarn can be more beneficial for concrete that do does not require high stress, while the knitted bars using glass fibres and polypropylene (50% and 50% PE) as core materials are not appropriate for applications that require more flexibility and extensibility. Reinforced concrete beams were improved significantly with cord-knitted bars, taking into account the number of bars per area, which may cause the minimizing of flexure force through an increase in that number of bars per area.
Keywords: cord-knitted, cement, construction, mortar, strength

Izvleček

Tehnične tkanine so zaradi mnogoterih lastnosti pomembne v številnih panogah. Namen te raziskave je bil uporabiti pletene kompozitne palice za ojačitev betonskih nosilcev. Pletene vrvice, izdelane iz polipropilenskih prej v zunanji plasti in jedra iz združenih prej, so bile potopljene v lokalno dostopno epoksismolo Kemapoxy 150. Izdelanih je bilo šest vzorcev pletenih kompozitnih palic iz dveh polipropilenskih prej različne dolžinske mase in s tremi različnimi jedri. Opravljenih je bilo več testiranj pletenih vrvic in pletenih kompozitnih palic. Vse meritve so bile statistično analizirane (ANOVA) in prikazane s pomočjo polarnih grafikonov. Izdelani so bili trije betonski nosilci z eno, dvema oziroma tremi pletenimi kompozitnimi palicami. Rezultati so pokazali, da različne preje v zunanji plasti in jedru pomembno vplivajo na lastnosti pletenih vrvic in pletenih kompozitnih palic. Pletene kompozitne palice z jedrom iz polipropilenske preje so primerne za betonske nosilce, ki ne zahtevajo velikih obremenitev. Pletene kompozitne palice iz steklenih vlaken oziroma iz 50 odstotkov polipropilenskih in 50 odstotkov polietilenskih vlaken niso primerne za aplikacije, kjer sta zahtevani

večja upogibljivost in raztegljivost betonskih nosilcev. Pletene kompozitne palice so izboljšale učinkovitost armiranih betonskih nosilcev, pri čemer je bila ugotovljena največja upogibna sila pri uporabi dveh palic na betonski nosilec.
Ključne besede: pletenina, cement, gradbeništvo, malta, trdnost

1 Introduction

Recent advances in textile production technology have led to its use in many applications, such as medical, agricultural, aerospace, filtering, etc., due to its unique properties. These textiles are known as technical textiles [1]. Technical textiles are defined as "Textile materials and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics" [1].

The corrosion of steel bars (rebar) used for reinforcing concrete is a major factor in reducing the service lifetime of reinforced concrete constructions. Thus, the solution is to cover or replace rebars with noncorrosive materials [2]. Textile reinforced concrete is a new advanced composite material. It generally comprises alkali-resistant fibreglass (AR) or carbon fibres with cementitious matrix reinforcement, in contrast to steel reinforcement. The single fibres of glass or carbon AR can be positioned in textile in any direction, which results in the adopted perfect orientation of an applied load [3].

The use of polypropylene fibres (PP) in concrete increases the concrete's tension and compressive strength [4, 5]. PP fibres are hydrophobic and have a melting point of about 160 °C [6]. When used in concrete, the yarns of PP create pathways in the concrete to evaporate moisture. PP fibres have been used in concrete to reduce cracking, increase toughness and impact resistance, and thus improve the energy absorption capacity of the concrete [7–9]. Many studies have shown that adding a small amount of PP fibres to fresh concrete can significantly reduce plastic cracking in the early stages, while these fibres can also significantly limit surface cracking and aggregate settlement in fresh concrete, reducing the possibility of setting cracks [7, 10].

Textile composites are stiff materials (enhanced by fibres, yarns and different fabric materials) that have properties, such as light weight, flexibility, solid construction and toughness. They have been employed for structural or load-bearing applications due to their outstanding quality [11, 12].

Rebars made of glass fibre-reinforced polymers provide various advantages over standard reinforced steel, including a higher ratio, greater corrosion resistance, and greater fatigue load resistance. A lack of ductility, however, is one of the key drawbacks of GFRP rebars [13, 14].

Fibre-reinforced polymers (FRP) provide special benefits to address a variety of civil engineering issues in situations when traditional materials fall short of expectations. Unlike steel, FRP can withstand the corrosive effects of acids, alkalis, salts, and other similar hostile compounds, without being damaged by electrochemical degradation. FRP is widely recognised as a steel substitute in applications where steel is susceptible to the significant risk of corrosion due to its superior properties, including high tensile strength and corrosion resistance [13, 14]. Tarek Elsayed *et al.* suggested the use of aramid, carbon and glass fibres via pultrusion to produce local rebars [14].

Knitting techniques usually give fabrics unique performance characteristics due to their yarn-looping shape [15, 16]. Those types of knitted fabrics have been employed as textile reinforced concrete (TRC) for concrete reinforcement in some studies [17]. In the same context, the cord-knitted fabric is considered one type of knitted fabric that is produced in a tube shape with different structures using a very small diameter of a circular knitting machine. Inlay warp, weft, and core yarns can be added for cord construction, where the final applications of the cord-knitted fabrics are affected by tightness factors [18].

The available commercial materials for the TRC system were basalt, carbon, glass and polyphenylene fabrics with different construction. Mortar must have fine grains, good workability, plastic consistency, low viscosity (to facilitate application on steep or vertical surfaces) and sufficient shear strength (to keep the composite material from peeling away from the substrate) [19, 20].

Taking into account earlier studies, this research aimed to utilize PP fibres to design and produce bars as a composite technique with a cord-knitted fabric for reinforcing concrete beams (which is an economical material for this application) and evaluate its performance.

2 Materials and methods

Six cord-knitted samples were fabricated with a plain structure and constructed with two layers (outer and core). Two different yarn counts from PP yarn (133 tex and 267 tex) were used for the outer layer, while three different materials with the closest yarn counts were used for the core layer as presented in Table 1. Figure 1 illustrates the experimentally manufactured cord-knitted samples and cross section.

2.1 Manufacture of cord-knitted samples

A cord-knitting machine with a cylinder diameter of 6 mm, and eight needles was used to manufacture the six polypropylene cord-knitted samples. Figure 2 shows a cord-knitting machine and its specifications.

2.2 Preparation of composite cord-knitted fabrics

Kemapoxy 150 (solvent-free, transparent epoxy) commercial resin from the company CMB was used for the preparation of composite bars as shown in

Figure 2: Cord knitting machine – internal cylinder diameter (cord diameter) = 6 mm

Quantity of needles: 8needles per diameter; machine speed: 800–1200 rpm; no creel needed and cones can be installed directly on the machine; automatic stop-motion system with tensioner configuration

(a) *(b)*

Figure 1: Cord-knitted fabrics: a) produced PP cord-knitted fabrics, b) cord-knitted cross section

Table 1: Experimental design of manufactured cord-knitted fabrics

Sample code	Outer layer		Core layer	
	Material	Yarn count (tex)	Material	Yarn count (tex)
1	PP a)	267	PP a)	approx. 156
2	PP a)	267	GF b)	
3	PP a)	267	50% PP/50% PE c)	
4	PP a)	133	PP a)	
5	PP a)	133	GF b)	
6	PP a)	133	50% PP/50% PE	

a) polypropylene, b) glass fibre, c) polyethylene

Figure 3. In order to prepare Kemapoxy 150, component B (hardener) was added to component A (resin) and manually mixed for three minutes. The cord-knitted fabrics were then immersed in a mixture for one minute, removed and put on a flat surface. The air was then vacuumed from the fabrics to obtain a stiffer shape and rough surface after drying.

(a) (b)

Figure 3: Coated samples (a) by Kemapoxy (b)

2.3 Reinforcement of concrete beams with composite cord-knitted bars

The concrete mix was prepared with the mixer shown in Figure 4 using the proportions presented in Table 2. One blank concrete beam and three groups of concrete beams measuring 50 cm × 10 cm × 10 cm were then produced. The first group of concrete beams was reinforced with one prepared PP cord-knitted bar, the second group of concrete beams was reinforced with two prepared PP cord-knitted bars and the third group of concrete beams was reinforced with three prepared PP cord-knitted. Figure 5 shows the pouring of reinforced prepared beams and Figure 6 shows reinforced concrete beams with PP prepared bars.

Figure 4: Concrete mix

Table 2: Proportions of concrete mix

Cement (kg)	Water (kg)	Super plasticizer (L)	Sand (kg)	Coarse aggregate (kg)
325	146	4.8	765	1145

Figure 5: Pouring reinforced beams with PP prepared bars

Figure 6: Reinforced concrete beams with PP prepared bars

2.4 Testing and analysis

Standard tests were used to test cord-knitted fabrics, composite bars and reinforced concrete beams, as described below.

2.4.1 Fabric testing

According to standard methods, tests were conducted on cord-knitted fabrics to determine their stitch length [21], tightness factor [22–26], longitudinal weight [27], thickness [28], bending length [29] and tensile force [30]. All tests were carried out according to standard conditioning, as described in test method BS 1051 for textile testing, where all samples were placed for 24 hours at a temperature of 20 °C ± 2 °C and a relative humidity (RH) of 65 % ± 2 %.

2.4.2 Testing of composite cord-knitted bars

At the national research centre, all prepared composite samples were examined for the bars' longitudinal weight [27], diameter and tensile force [31], in accordance with standard methods to investigate any potential effects on the application of reinforced concrete beams.

2.4.3 Testing of reinforced concrete beams

One of the key metrics for describing concrete strength is flexure strength. It is a measurement of a beam's or slab's resistance to bending failure. According to the ASTM C293 standard test method (centre point loading) [32], flexure strength is tested in the lab of the Housing and Building National Research Centre by applying a point load to concrete beams in the middle of a span length. Figure 7 shows the flexure of a beam that has been reinforced with bars made from PP cord-knitted textiles.

Figure 7: Flexure point load test of reinforced beam with the PP cord-knitted bars

2.5 Data analysis

All results were collected and analysed using two different tools: an ANOVA test with a P-value of ≤ 0.05 was performed in order to identify the significant/insignificant effect of different variables on the production of bars, while a radar chart area was calculated and plotted in order to rank the samples and assign the preferable performance characteristics.

3 Results and discussion

3.1 Physical and mechanical characterizations

Cord-knitted samples were tested and tabulated to compare their characteristics, as shown in Table 3. The findings show that the cord-knitted bars with a core PP yarn (samples No. 1 and 4) achieved the lowest fabric thickness and fabric tensile force, as well as the highest tightness factor and elongation percentage relative to other cord-knitted samples. Furthermore, the cord-knitted bars with core glass fibres (GF) (samples No. 2 and 5) attained the highest fabric weight/length at one meter and the lowest elongation, while the cord-knitted bars with a core of 50% PP/50% PE (samples No. 3 and 6) achieved the highest fabric thickness, bending length and tensile force. The reason can be traced to variation in the density and elasticity of the core yarns, which are seen in several knitted-bar characteristics.

As a result of the above, prepared composite bars of cord-knitted samples were tested, and the findings are presented in Table 4. The findings show that the bar samples prepared with PP as a core material achieved the lowest weight, diameter and tensile force (N). On the other hand, the bar samples prepared with GF achieved the highest weight, medium diameter and tensile force, while the bar samples prepared

Table 3: Tests results of PP cord-knitted samples

No.	Stitch length (cm)	Tightness factor	Weight (kg)	Thickness (mm)	Bending length (cm)	Tensile force (N)	Elongation (%)
1	0.2	5.74	0.147	5.1	33.5	1120	32.77
2	0.228	5.03	0.163	5.8	40	1670	4.32
3	0.247	4.65	0.126	6.3	40	2190	18.73
4	0.251	6.47	0.189	6.4	32.5	1180	73.32
5	0.255	6.37	0.218	6.5	37	1290	5.25
6	0.286	5.68	0.167	7.3	42.5	2990	59.92

with 50% PP/50% PE achieved a medium weight, and the highest bar diameter and tensile force, emphasizing the unique and significant effect of core yarns on the characteristics of bar samples.

Table 4: Tests results of PP cord-knitted prepared bars

Sample no.	Bar weight (kg)	Bar diameter (mm)	Bar tensile force (N)
1	0.028	5.9	1800
2	0.033	5.9	2620
3	0.032	6.3	3370
4	0.031	6.5	1770
5	0.037	6.7	2240
6	0.034	7.3	3360

3.2 Significant/insignificant effect

In order to explain the effect of different variables in the production of samples, an ANOVA test with a P-value of ≤ 0.05 was performed, with the results shown in Tables 5 and 6. The results indicate that the difference in outer PP yarn count (133 tex and 267 tex) has a significant effect on the stitch length, weight and thickness characteristics of cord-knitted samples, and on the diameter characteristic of the prepared composite bars. Moreover, the results indicate that the variation of core yarns only had significant effect on the fabric weight of the cord-knitted fabric, and on the tensile force of the prepared composite bars.

Table 5: ANOVA results of PP cord-knitted samples

Characteristics	P-value	
	Outer count yarns	Core materials
Stitch length (mm)	0.030139 [a)]	0.077754
Sample weight (g)	0.008714 [a)]	0.028537 [a)]
Sample thickness (mm)	0.028714 [a)]	0.074176
Sample bending length	0.785166	0.098936
Sample tensile force (kN)	0.687811	0.135106
Sample elongation (%)	0.174346	0.176963

[a)] Significant effect

3.3 Ranking of samples

In order to determine preferable performance characteristics, radar chart areas were calculated and plotted for all samples, as shown in Figure 8 and Table 7. The results indicate that the cord-knitted sample No. 6 (PP 266 tex, 50% PP/50% PE core yarn) achieved the highest behavioural characteristics, while the cord-knitted sample No. 5 (PP 133 tex, GF core yarn) recorded the lowest. Moreover, the results indicate that the cord-knitted sample No. 1 with a core yarn PP and outer PP yarn count of 133 tex ranked highest among other samples with the same outer PP yarn count, while the cord-knitted sample with a core yarn PP and outer PP yarn count of 266 tex ranked second. We can thus conclude that the PP yarns had a significant effect on produced cord-knitted performance characteristics.

Table 6: ANOVA results of PP cord-knitted prepared bars

Characteristics	P-value	
	Outer count yarns	Core materials
Bars' weight (g)	0.31687	0.269231
Bars' diameter (mm)	0.020204 a)	0.088235
Bars' tensile force (kN)	0.364074	0.016863 a)

[a)] Significant effect

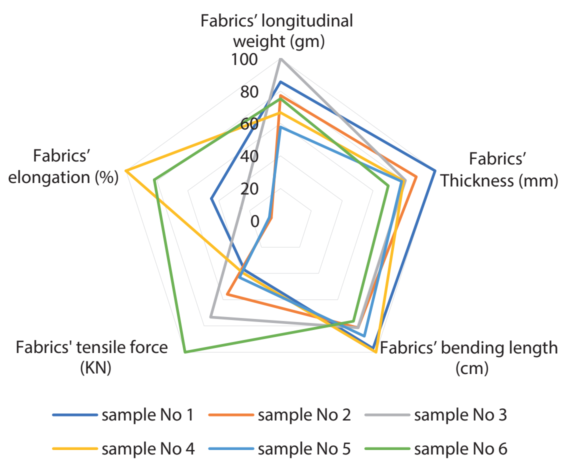

Figure 8: Radar chart for PP cord-knitted fabric samples

At the same time, radar chart areas for prepared composite bars were calculated and plotted, as seen in Figure 9 and Table 8. The result indicate that samples with 50% PP/50% PE core yarn ranked highest at different yarn counts of outer PP yarn, while samples with PP core yarn ranked lowest at different outer PP yarn counts, despite achieving a preferable rank among cord-knitted samples. This could be attributed to the decreasing tensile force of PP yarns compared with other materials (glass fibres and 50% PP/50% PE), an indication that its

Table 7: Radar chart for PP cord-knitted fabrics

Sample no.	Weight (%)	Thickness (%)	Bending length (%)	Tensile force (%)	Elongation (%)	Radar chart area	Rank
1	85.7	100	97.01	37.4	44.6	26070.41	3
2	77.2	87.9	81.2	55.8	5.89	18312.8	5
3	100	80.9	81.2	73.2	25.5	23823.32	4
4	66.6	79.6	100	39.4	100	26478.26	2
5	57.7	78.4	87.8	43.1	7.16	15159.14	6
6	75.1	69.8	76.4	100	81.7	30964.57	1

Table 8: Radar chart area calculation for prepared bars

Sample no.	Weight (g)	Thickness (mm)	Bar tensile force (kN)	Radar chart area	Rank
1	100	100	53.4	17911.6	5
2	84.8	100	77.7	19793.8	2
3	87.5	93.7	100	22784.7	1
4	90.3	90.8	52.5	15337.2	6
5	87.5	88	66.5	16778.8	4
6	75.7	80.8	99.7	18809.7	3

potential use in various applications does not require high stress. At the same time, the other materials may be inappropriate for applications requiring more flexibility and extensibility.

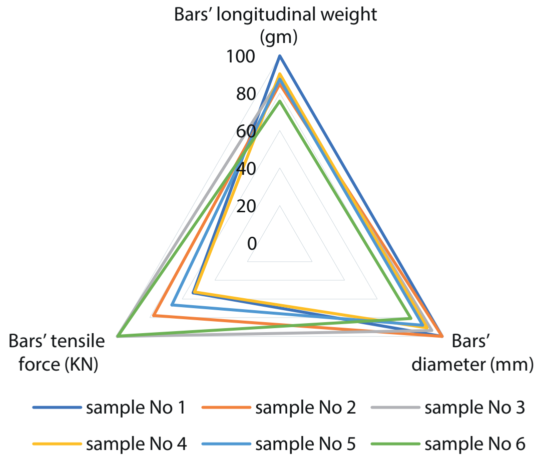

Figure 9: Radar chart for PP prepared bars

3.4 Results for reinforced concrete beams

Concrete beams reinforced with composite PP cord-knitted bars (PP 133 tex, PP core yarn) were produced. Three different composite cord-knitted bars (one, two and three bars) were applied to concrete beams, while a basic concrete bar without cord-knitted fabric was also tested. The flexure forces of basic and reinforced concrete beams were tested, as shown in Table 9. The results confirm that, although PP bars (PP core yarn, PP outer yarn) achieved the lowest tensile force (kN) as seen in Table 3, they enhanced reinforced concrete beams using varying numbers of cord bars, indicating that other prepared cord-knitted bars with altered cores yarn could further improve reinforced concrete beams. Additionally, the results indicate that the number of bars per area impacts the flexure force of reinforced concrete beams, as exceeding a certain limit might reduce flexure force, where beam No. 3 with three bars achieved the lowest force and beam No. 2 with two bars achieved the highest force.

Table 9: Flexure force results for concrete beams reinforced with polypropylene cord-knitted prepared bars

Sample no.	Number of bars	Reinforcing bar material	Flexure force (kN)
Basic	0	No reinforcing	10.5
Beam 1	1	PP	14.7
Beam 2	2	PP	15.7
Beam 3	3	PP	13.5

4 Conclusion

Based on the results reported in this study regarding the use of cord-knitted PP fabrics to reinforce concrete beams, the following main conclusions can be drawn:

- The variance of outer PP yarn count (133 tex and 266 tex) and core yarns has a significant effect on several cord-knitted fabric and bar characteristics.
- Although the cord-knitted fabric with PP outer and core yarns did not achieve the highest results (depending on radar area), it did have a significant effect on the samples' performance characteristics.
- According to the testing of knitted bars, the potential use of bars with PP core can be excluded for applications that require high stress. On the other hand, the knitted bars with core materials glass fibres and 50% PP/50% PE are not suitable for applications requiring more flexibility and extensibility.
- Cord-knitted bars enhanced reinforced concrete beams effectively, while the number of bars per area should be considered during the production of reinforced concrete beams, as exceeding a certain limit might reduce flexure force.

Acknowledgement

The authors would like thank the National Research Centre and the Housing and Building National Research Centre for testing the samples from this study in their labs.

References

1. *Handbook of technical textiles*. Edited by A. R. Horrocks and S. C. Anand. Cambridge : Woodhead Publishing, 2000, 1–4.
2. PARK, K.T., KIM, H.Y., YOU, Y.J., LEE, S.Y., SEO, D.W. Hybrid FRP reinforcing bars for concrete structures. In *4th Asia-Pacific Conference on FRP in Structures, Melbourne, 2013*. Ontario : International Institute for FRP in Construction, 2013.
3. BRÜCKNER, A., ORTLEPP, R., CURBACH, M. Textile reinforced concrete for strengthening in bending and shear. *Materials and Structures*, 2006, **39**(8), 741–748, doi: 10.1617/s11527-005-9027-2.
4. KURBAK, A., SOYDAN, A.S. Geometrical model for a newly designed three-dimensional functional rib-knitted cord. *Textile Research Journal*, 2013, **83**(9), 971–990, doi: 10.1177/0040517512461702.
5. AL-KATIB, H.A., ALKHUDERY, H.H., AL-TAMEEMI, H.A. Behavior of polypropylene fibers reinforced concrete modified with high performance cement. *International Journal of Civil Engineering and Technology (IJCIET)*, 2018, **9**(5), 1066–1074.
6. RAMUJEE, K. Strength properties of polypropylene fiber reinforced concrete. *International Journal of Innovative Research in Science, Engineering and Technology*, 2013, **2**(8), 3409–3413.
7. MOHOD, M.V. Performance of polypropylene fibre reinforced concrete. *IOSR Journal of Mechanical and Civil Engineering*, 2015, **12**(1), 28–36.
8. OZGER, O.B., GIRARDI, F., GIANNUZZI, G.M., SALOMONI, V.A., MAJORANA, C.E., FAMBRI, L., DI MAGGIO, R. Effect of nylon fibres on mechanical and thermal properties of hardened concrete for energy storage systems. *Materials & Design*, 2013, **51**, 989–997, doi:10.1016/2013.04.085.
9. ALTOUBAT, Salah, YAZDANBAKHSH, Ardavan, RIEDER, Klaus-Alexander. Shear behaviour of macro-synthetic fibre-reinforced concrete beams without stirrups. *Materials Journal*, 2009, **106**(4), 381–389, doi: 10.14359/56659.
10. NILI, M., AFROUGHSABET, V. The effects of silica fume and polypropylene fibres on the impact resistance and mechanical properties of concrete. *Construction and Building Materials*, 2010, **24**(6), 927–933, doi: 10.1016/j.conbuildmat.2009.11.025.
11. YAO, W., ZHONG, W. Effect of polypropylene fibres on the long-term tensile strength of concrete. *Journal of Wuhan University of Technology – Materials Science Edition*, 2007, **22**(1), 52–55, doi:10.1007/s11595-005-1052-z.
12. PORTAL, N.W. *Usability of textile reinforced concrete: structural performance, durability and sustainability. PhD thesis*. Gothenburg : Chalmers University of Technology, Department of Civil and Environmental Engineering, Division of Structural Engineering Concrete Structures, 2015.
13. ELGORY, Z.M., ISMAIL ABD EL-AZIZ, M.Y. Use of textile nets to reinforce concrete elements. *Egyptian Journal of Chemistry*, 2022, **65**(131), 919–924, doi: 10.21608/ejchem.2022.127989.5892.

14. ELSAYED, Tarek A., ELHEFNAWY, Amr A., ELDALY, Amr A., GHANEM, Gouda. Hybrid fibre reinforced polymers rebars. *Journal of Advanced Materials – Covina*, 2011, **43**(1), 65–75.
15. RICHARDSON, A., DREW, P. Fibre reinforced polymer and steel rebar comparative performance. *Structural Survey*, 2011, **29**(1), 63–74, doi:10.1108/02630801111118412.
16. ELGORY, Z.M., SEDDIK, K.M., YAHIA, M., EL-GABRY, L.K. The enhancement of the functional properties of polyester microfiber single jersey using some nano-materials. *Egyptian Journal of Chemistry*, 2020, **63**(1), 145–154, doi: 10.21608/ejchem.2019.2868.1804.
17. ABDEL-MEGIED, Z.M., KM, S., EL-AZIZ, M.Y.A. Improve UV protection property of single jersey for summer protective clothes. *Journal of Textile & Apparel Technology & Management (JTATM)*, 2018, **10**(3), 1–9.
18. FRAAS, V. First national technical approval for textile-reinforced concrete [online]. BFT International [accessed 25. 4. 2023]. Available on World Wide Web: <https://www.bft-international.com/en/artikel/bft_First_national_technical_approval_for_textile-reinforced_concrete-2051230.html>.
19. PANDEY, A. *Manufacture of advanced textile composites: project*. Glasgow : University of Glasgow, 2009-2011.
20. CHUDOBA, R., VOŘECHOVSKÝ, M., KONRAD, M. Stochastic modeling of multi-filament yarns. I. Random properties within the cross-section and size effect. *International Journal of Solids and Structures*, 2006, **43**(3-4), 413–434, doi: 10.1016/j.ijsolstr.2005.06.063.
21. BS 5441:1988. Methods of test for knitted fabrics. London : BSI Group, 1988.
22. VENKATARAMAN, K. Study on geometric and dimensional properties of double pique knitted fabrics using cotton sheath elastomeric core yarn. *Journal of Textile and Apparel, Technology and Management*, 2014, **8**(4), 2014, 1–13.
23. GRAVAS, E., KIEKENS, P., VAN LANGENHOVE, L. Predicting fabric weight per unit area of single and double-knitted structures using appropriate software. *AUTEX Research Journal*, 2006, **6**(4), 223–237.
24. MUNDEN, D.L. The geometry and dimensional properties of plain-knit fabrics. *Journal of the Textile Institute Transactions*, 1959, **50**(7), T448–T471, doi: 10.1080/19447025908659923.
25. ABRAMAVIČIŪTĖ, J., MIKUČIONIENĖ, D., ČIUKAS, R. Structure properties of knits from natural yarns and their combination with elastane and polyamide threads. *Materials Science*, 2011, **17**(1), 43–46, doi: 10.5755/j01.ms.17.1.247.
26. ICHETAONYE, S.I., ICHETAONYE, D.N., OWEN, M.M., AWOSANYA, A., DIM, J.C. Effect of stitch length on the physical properties of (3x1, 4x1, 5x1, 6x1) rib knitted fabrics. *International Journal of Fibre and Textile Research*, 2013, **3**(3), 63–65.
27. ASTM D3776. Standard test methods for mass per unit area (weight) of fabric. West Conshohocken : ASTM International, 2020.
28. ASTM D1777. Standard test method for thickness of textile materials. West Conshohocken : ASTM International, 2019.
29. ASTM D1388. Standard test method for stiffness of fabrics. West Conshohocken : ASTM International, 2018.
30. ASTM D4268. Standard test methods for testing fibre ropes. West Conshohocken : ASTM International, 2002.
31. ISO 15630-1. Steel for the reinforcement and prestressing of concrete - test methods - part 1: reinforcing bars, rods and wire. Geneva : International Organization for Standardization, 2019.
32. ASTM C293. Standard test method for flexural strength of concrete. West Conshohocken : ASTM International, 2016.