

COMPRESSION OF FOLDABLE LINKS-LINKS KNITTED STRUCTURES

KATLANABİLİR HAROŞA YAPILARIN SIKIŞTIRILABİLİRLİK ÖZELLİĞİ

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ABSTRACT

Folding of links-links knitted structures is based on the structural disequilibrium of face and reverse loops, which causes the fabric to form a 3-dimensional structure. Foldable structures shrink in both course and wale directions when relaxed. Under the applied strain in the horizontal or vertical direction, 3-dimensional structures smooth into a flat fabric, creases unfold and the structures expand in both directions. Fabric thickness increases with folding. Compressibility means a decrease in initial thickness due to the increase in compressive force at measuring time. It is affected by knitting parameters such as density, fabric thickness, texture etc. The aim of the research was to evaluate the compressibility of links-links weft knitted fabrics with a zigzag structure which could potentially be used as a packaging and mechanical damage protection material. The influence of the yarn material composition and repeat size on the compression properties of foldable links-links knitted structures was examined in order to evaluate their adequacy for compression resistant materials.

Keywords: Compression, Foldable structures, Auxetic potential, Poisson's ratio, Links-links, Knitted fabric, Weft knitting

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1. INTRODUCTION

Foldable knitted structures are flat when extended and 3-dimensional when collapsed. They are distinguished by their attractive spacer appearance, multi-use and multi-function potential and possible unconventional properties. Opposite to woven and nonwoven textiles, which usually exhibit a folded look achieved with sewing or finishing, foldable knits can be designed by integrating folds directly into the knitted structure. Folded knits can involve a wide range of structures from simple ribs and pleats to more complex 3-dimensional structures.

Links-links knitting enables manufacturing of very aesthetically intriguing structures which are flat knitted but crease and fold after the relaxation, forming various textures and spatial patterns. The folding of links-links knitted structures is based on the structural disequilibrium of face and reverse loops, which causes the fabric to crease, contract and form a 3-dimensional structure after the knitting process. Foldable structures shrink in both course and wale directions. Under the applied strain in the horizontal or vertical direction, 3-dimensional foldable structures smooth

into a flat fabric, creases unfold and the structures expand in both directions. Foldable links-links knitted structures can be designed in various patterns. A zigzag links-links repeat results in a zigzag folded structure after the relaxation (Figure 1).

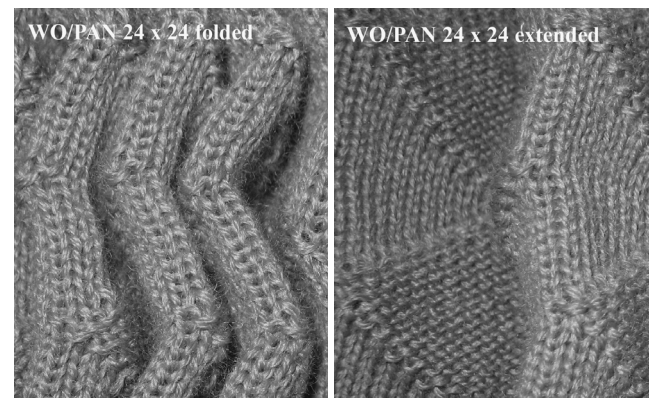


Figure 1. Folded and unfolded/extended zigzag knitted structure with 24 × 24 square repeat

3-dimensional foldable weft knitted structures exhibit extreme versatility and multi-functionality. They offer new, relief surfaces, appropriate for use for packaging and shock absorbing materials. The folding potential enables a good fit to the content and adequate protection of goods from external damages. In their research, Liu et al (1) concluded that the fabric thickness is influenced by the folding process. A higher fabric thickness means a more closely folded structure.

Compression is one of the important fabric properties, in addition to friction, bending, tension and shear. Compression may be defined as a decrease in intrinsic thickness with an appropriate increase in pressure. Intrinsic thickness is the thickness of space occupied by a fabric subjected to barely perceptible pressure. The applied compressive force allows the yarn to undergo deformation non-linearly, resulting in the change of fabric thickness (2). The relationship between the applied force (normal to fabric plane) per unit area and the resulting fabric thickness can be obtained with a simple test. The tested fabric specimen is placed horizontally on a platter, and subsequently loaded and unloaded with a presser foot. The fabric thickness, which is the distance between the presser foot and the platter, is recorded as the function of applied pressure. This pressure-thickness relationship describes the compression characteristic of the fabric. The pressure-thickness curve of textile fabrics in lateral compression is highly non-linear (3).

The compressibility behaviour of knitted and woven fabrics depends on a number of factors, i.e. fabric tightness, fabric surface irregularity, yarn hairiness, yarn compressibility, fibre material etc. The analyses of the pressure-thickness relationship performed by Alimaa et al (4) demonstrated a very prominent effect in terms of the knit construction and yarn structure. It was observed that fabric compressibility primarily depended on the fibre material. The composition properties of knitted fabrics were also essentially due to their knit constructions. Moreover, the loop length determined the compressibility of knitted fabrics to a great extent (4). Fabric compression involves the movement of fibres and yarns within the diameter axis to which the fabric is oriented. This behaviour is accounted for by studying the fabric internal non-linear structure, the visco-elastic nature of fibres themselves, and, to some extent, the friction between the fibres and yarns (2).

The compression characteristics of fabrics, along with bending, tensile, shear and surface characteristics, are closely related to fabric handle, drape and tailorability or making-up properties. The fabric that compresses easily is likely to be judged as soft, possessing a low compression modulus or high compression. The compression property of a fabric also plays an important role in comfort (2).

Many researchers have studied the compression characteristics of knitted fabrics. The low load compression behaviour of textiles has been examined in order to evaluate their comfort and handle properties, while high pressure compressibility has been studied to assess the shock absorbing and surface protection potential. Lately, the research has been focused on spacer knitted fabrics and composites (5–9). There has been no evidence of the foldable knitted structures compressibility research.

The aim of the presented study was to evaluate the behaviour of links-links weft knitted fabrics with a zigzag structure under compression. The examined structures could potentially be

used as a packaging and mechanical damage protection material. The influence of yarn material composition and the structural parameters of foldable structures, such as repeat size, i.e. width/height ratio, on the compression properties of foldable links-links knitted structures were examined in order to evaluate their adequacy for compression resistant materials. The compression behaviour of examined foldable structures was compared to some selected actual compression materials used in packaging, such as bubble foil, textured rubber foam and woollen felt (Figure 7).

2. MATERIALS AND METHODS

2.1 Sample preparation

The study of the influence of the unit cell size as well as the zigzag rib width of knitted structures on their compression properties was performed. The repeat size and the form of primary samples originated from the repeat of knitted samples examined by Liu et al (1). From the primary 24×24 repeat size, two series of sample sizes and forms were designed (Figure 2).

The first series of zigzag knitted structures was produced in various unit cell sizes with the same number of courses and wales in a zigzag form from the smallest 4×4 to the largest 24×24 repeat size (Figures 3 and 5), while the second series was produced with various widths of the zigzag line in a unit cell with a constant number of courses from the narrowest 4×24 to the widest 24×24 repeat size (Figures 4 and 6). Figures 3-6 show some selected samples.

Both series of knitted structures were produced from two different yarns (Figure 2). The first one was a blend of 46.38% wool (Wo) and 53.62% polyacrylonitrile (PAN) with the linear density of 70.54 tex. The second one was a blend of 86.38% viscose (CV) and 13.62% polyamide (PA) with the linear density of 74.78 tex. The linear density of the yarns was determined by the SIST EN ISO 2060: 1999 standard method. The material composition of the yarns was determined by the SIST ISO 1833: 2009 standard method.

The samples were knitted on a Shima Seiki SES122RT knitting machine, gauge12E with the cam position set to the value 35. The dimensions of specimens were 344 wales (needles) \times 672 courses. Two specimens were produced for each knitted structure. After the removal from the knitting machine, specimens folded into 3-dimensional structures. The compression tests were performed after the samples were relaxed for several days. Five measurements were carried out at five different locations of each specimen.

In previous investigations, it was established (10) that with the second series of samples, the width of zigzag lines distinctively influences the ability to fold; the structures made of Wo/PAN fully fold from the unit cell repeats 24×24 to 16×24 , while the structures made of CV/PA fully fold from the unit cell repeats 24×24 to 14×24 . Therefore, only the compression properties of fully folded knitted structures were examined due to their protective packaging potential.

In addition to knitted structures, some actual packaging materials were selected and investigated (Figure 7). Their compression properties were analysed compared to the compression properties of the foldable knitted structures in order to evaluate the potential usability of the foldable knitted structures for packaging and damage protection material.

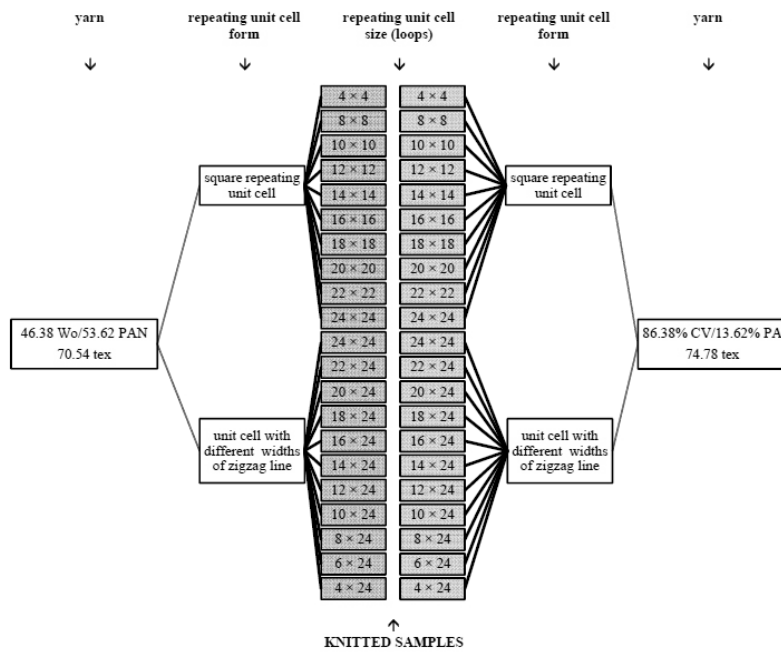


Figure 2. Knitted samples preparation diagram

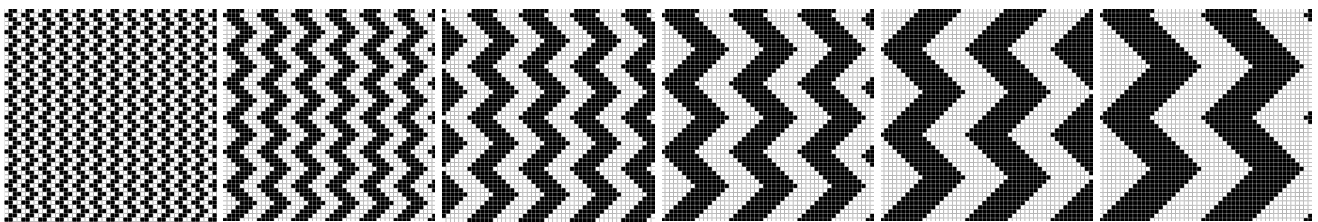


Figure 3. Pattern chart of selected zigzag knitted structures with different square repeating unit cell sizes (size of repeating unit cell from left to right: 4×4 , 8×8 , 12×12 , 16×16 , 20×20 and 24×24)

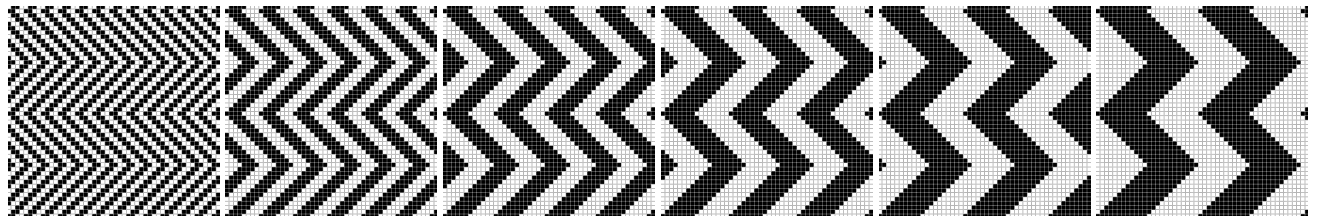


Figure 4. Pattern chart of selected zigzag knitted structures with different widths of zigzag line (size of repeating unit cell from left to right: 4×24 , 8×24 , 12×24 , 16×24 , 20×24 and 24×24)

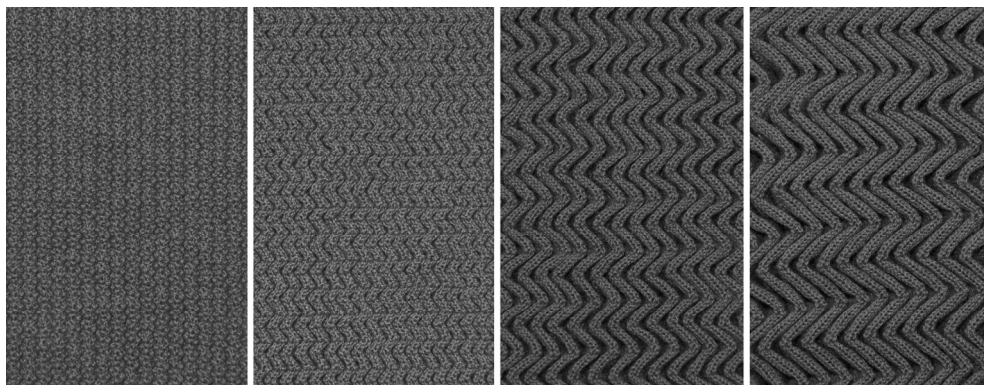


Figure 5. Selected zigzag knitted structures with varying unit cell sizes made of WO/PAN yarn (size of repeating unit cell from left to right: 4×4 , 8×8 , 16×16 and 24×24)

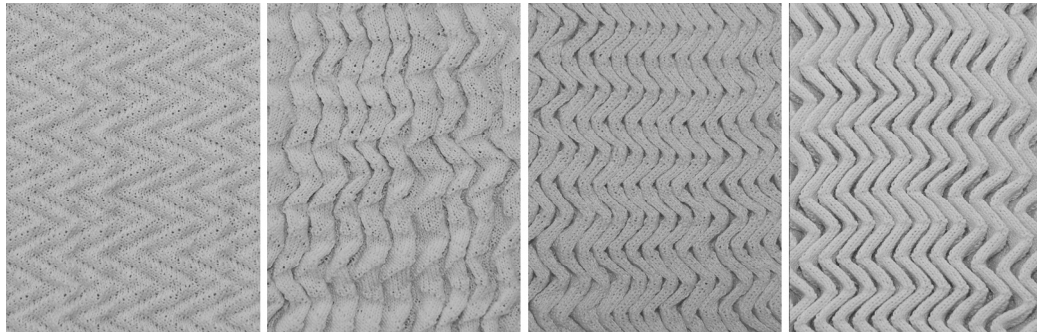


Figure 6. Selected knitted structures with varying width of zigzag line and constant number of courses made of CV/PA yarn (size of repeating unit cell from left to right: 8 × 24, 14 × 24, 16 × 24 and 24 × 24)

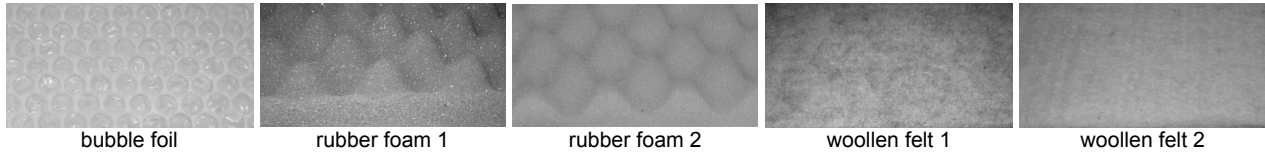


Figure 7. Investigated actual compression materials used in packaging: bubble foil, textured rubber foam and woollen felt

2.2 Test methods and procedures

First, the compression test was performed on a dynamometer INSTRON 5567 based on the Bluehill® software compression application module. The speed of the movable pressure foot was 0.3 mm/s. The compression load was read when the distance between the movable pressure foot and the fixed flatten reached 1 mm. A circular pressure foot with 9 cm in diameter was used. Ten measurements of the maximum compressive load at the compressed thickness of the knitted structure $t_{\text{compr}} = 1$ mm for each sample were performed.

Then, the thickness of the knitted structures and comparative materials was measured in a separate testing procedure. Due to the 3-dimensional foldable structure of examined knitted fabrics, the thickness was read from the compression curve. The test was performed on a

dynamometer INSTRON 5567. The speed of the movable pressure foot was adjusted to 0.1 mm/s to detect the contact of the movable pressure foot and the fabric surface. The maximum compression load was set to 10 N. When the compression load was detected, the distance between the clamps was read from the compression curve. Five measurements for each sample were performed.

Mass per unit area of the samples was determined by the SIST ISO 3801: 1996 standard method.

3. RESULTS AND DISCUSSION

The results of the maximum compression load, fabric thickness and mass per unit area measurements are presented in Tables 1 and 2. The results of compressive stress at the maximum compression load are presented in Figures 8–10.

Table 1. Maximum compression load and fabric thickness for foldable zigzag knitted structures with same number of courses and wales in unit cell repeat (first series of samples, Figures 3 and 5)

| repeat | CV/PA | | | | | | Wo/PAN | | | | | |
|---------|----------------------|-------|----------------|------|---|------|----------------------|-------|----------------|------|---|------|
| | max. compr. load (N) | | thickness (mm) | | mass per unit area (gcm ⁻²) | | max. compr. load (N) | | thickness (mm) | | mass per unit area (gcm ⁻²) | |
| | mean | cv | mean | cv | mean | cv | mean | cv | mean | cv | mean | cv |
| 24 × 24 | 6526.36 | 12.48 | 18.02 | 0.45 | 2203.67 | 2.94 | 4408.17 | 9.27 | 19.49 | 1.43 | 1988.61 | 5.92 |
| 22 × 22 | 6005.64 | 9.23 | 16.67 | 1.98 | 2119.01 | 2.90 | 3503.05 | 5.49 | 18.11 | 2.40 | 1909.49 | 4.34 |
| 20 × 20 | 5807.19 | 8.89 | 15.15 | 1.46 | 2021.27 | 2.00 | 2829.05 | 7.70 | 16.90 | 2.03 | 1671.85 | 1.3 |
| 18 × 18 | 5144.61 | 11.57 | 14.46 | 1.77 | 1906.21 | 3.04 | 2368.65 | 15.87 | 16.02 | 1.66 | 1570.92 | 3.17 |
| 16 × 16 | 4911.03 | 6.81 | 12.61 | 1.39 | 1838.06 | 1.69 | 1993.34 | 14.01 | 14.46 | 1.61 | 1403.97 | 2.10 |
| 14 × 14 | 4553.02 | 6.48 | 11.37 | 1.91 | 1699.20 | 5.81 | 1229.51 | 9.55 | 12.57 | 2.98 | 1234.09 | 3.61 |
| 12 × 12 | 3573.88 | 7.28 | 9.83 | 1.03 | 1487.06 | 3.55 | 1087.91 | 12.08 | 11.30 | 1.35 | 1175.68 | 1.88 |
| 10 × 10 | 2732.81 | 6.78 | 8.39 | 1.18 | 1342.19 | 1.13 | 806.15 | 8.04 | 10.00 | 2.01 | 1090.40 | 2.57 |
| 8 × 8 | 1627.38 | 6.80 | 7.14 | 3.11 | 1078.53 | 2.30 | 574.16 | 6.44 | 8.55 | 3.42 | 926.23 | 1.63 |
| 6 × 6 | 753.70 | 8.57 | 5.86 | 1.69 | 835.66 | 1.82 | 300.97 | 2.77 | 6.98 | 1.08 | 743.63 | 1.70 |
| 4 × 4 | 174.65 | 8.51 | 4.49 | 4.25 | 588.66 | 1.35 | 103.89 | 6.54 | 5.64 | 3.78 | 551.61 | 2.96 |
| foil | 220.84 | 11.18 | 3.47 | 4.79 | 40.61 | 0.50 | 220.84 | 11.18 | 3.47 | 4.79 | 40.61 | 0.50 |
| felt 1 | 2392.86 | 9.03 | 6.61 | 4.11 | 513.09 | 0.72 | 2392.86 | 9.03 | 6.61 | 4.11 | 513.09 | 0.72 |
| felt 2 | 9156.20 | 6.43 | 11.44 | 6.7 | 1119.56 | 0.33 | 9156.20 | 6.43 | 11.44 | 6.7 | 1119.56 | 0.33 |
| foam 1 | 679.67 | 6.27 | 22.69 | 1.03 | 291.10 | 4.00 | 679.67 | 6.27 | 22.69 | 1.03 | 291.10 | 4.00 |
| foam 2 | 775.06 | 6.80 | 26.83 | 0.90 | 319.66 | 0.79 | 775.06 | 6.80 | 26.83 | 0.90 | 319.66 | 0.79 |

Table 2. Maximum compression load of foldable zigzag knitted structures with different widths of zigzag line and constant number of courses in unit cell repeat (second series of samples, Figures 4 and 6)

| repeat | CV/PA | | | | | | Wo/PAN | | | | | |
|---------|----------------------|-------|----------------|------|---|------|----------------------|-------|----------------|-------|---|------|
| | max. compr. load (N) | | thickness (mm) | | mass per unit area (gcm ⁻²) | | max. compr. load (N) | | thickness (mm) | | mass per unit area (gcm ⁻²) | |
| | mean | cv | mean | cv | mean | cv | mean | cv | mean | cv | mean | cv |
| 24 × 24 | 6526.36 | 12.48 | 18.02 | 0.45 | 2203.67 | 2.94 | 4408.17 | 9.27 | 19.49 | 1.43 | 1988.61 | 5.92 |
| 22 × 24 | 6236.32 | 10.81 | 16.29 | 0.60 | 2113.72 | 3.44 | 3888.23 | 9.87 | 18.38 | 2.14 | 1822.99 | 1.61 |
| 20 × 24 | 5581.71 | 8.85 | 16.16 | 0.93 | 2006.84 | 3.44 | 2815.86 | 7.46 | 17.12 | 0.96 | 1691.03 | 3.54 |
| 18 × 24 | 5408.08 | 8.01 | 14.61 | 2.09 | 1871.30 | 0.98 | 2176.13 | 8.18 | 16.16 | 2.75 | 1515.80 | 1.75 |
| 16 × 24 | 3418.32 | 13.99 | 13.09 | 1.68 | 1592.92 | 3.14 | 464.03 | 20.36 | 14.10 | 3.50 | 1016.22 | 1.51 |
| 14 × 24 | 570.48 | 13.60 | 10.89 | 1.54 | 826.01 | 2.50 | 141.77 | 12.51 | 9.68 | 10.89 | 644.02 | 4.38 |
| foil | 220.84 | 11.18 | 3.47 | 4.79 | 40.61 | 0.50 | 220.84 | 11.18 | 3.47 | 4.79 | 40.61 | 0.50 |
| felt 1 | 2392.86 | 9.03 | 6.61 | 4.11 | 513.09 | 0.72 | 2392.86 | 9.03 | 6.61 | 4.11 | 513.09 | 0.72 |
| felt 2 | 9156.20 | 6.43 | 11.44 | 6.7 | 1119.56 | 0.33 | 9156.20 | 6.43 | 11.44 | 6.7 | 1119.56 | 0.33 |
| foam 1 | 679.67 | 6.27 | 22.69 | 1.03 | 291.10 | 4.00 | 679.67 | 6.27 | 22.69 | 1.03 | 291.10 | 4.00 |
| foam 2 | 775.06 | 6.80 | 26.83 | 0.90 | 319.66 | 0.79 | 775.06 | 6.80 | 26.83 | 0.90 | 319.66 | 0.79 |

A previous investigation of the folded fabrics' thickness (11), summarized in Tables 1 and 2, showed that the knitted structures with a higher repeat are thicker. Furthermore, the knitted structures made from Wo/PAN yarn are thicker than the knitted structures made from CV/PA yarn (11). Thickness of the CV/PA investigated knitted structures ranges from 4.49 mm to 18.02 mm. Thickness of the Wo/PAN investigated knitted structures ranges from 5.64 mm to 19.49 mm. Thickness of the comparative packaging materials ranges from 3.47 mm to 26.83 mm.

It can be seen from the Tables 1 and 2 that the knitted structures with a higher repeat exhibit higher mass per unit area which can be contributed to their higher thickness. Furthermore, the knitted structures made from CV/PA yarn exhibit higher mass per unit area than the knitted structures made from Wo/PAN yarn which can be contributed to higher specific gravity of CV fibres. Mass per unit area of the CV/PA investigated knitted structures ranges from 588.66 gcm⁻² to 2203.67 gcm⁻². Mass per unit area of the Wo/PAN investigated knitted structures ranges from 551.61 gcm⁻² to 1988.61 gcm⁻². Mass per unit area of the comparative packaging materials ranges from 40.61 gcm⁻² to 1119.66 gcm⁻². Mass per unit area of the bubble foil, rubber foam and thinner woollen felt (sample "felt 1") is substantially lower than the mass per unit area of the investigated knitted structures with the comparable thickness.

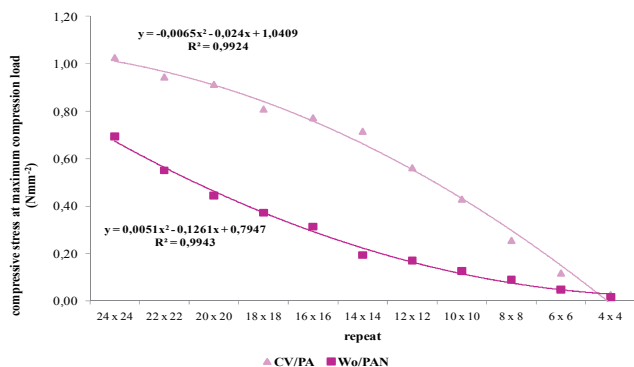


Figure 8. Compressive stress at maximum compression load for foldable zigzag knitted structures with same number of courses and wales in unit cell repeat

The results of the previous investigation (11) were considered in the analysis of foldable structures compression properties.

The zigzag folded knitted structures with the square repeat comprising the same number of courses and wales (first series of samples) fully folded in both course and wale direction. Full folding emerged for all repeat sizes and structures produced from both yarns. The structures designed with various widths of zigzag ribs (second series of samples) exhibited a substantial deterioration for smaller repeats; the structures with the rib widths smaller than 7 loops were very poorly folded; their thickness decreased significantly.

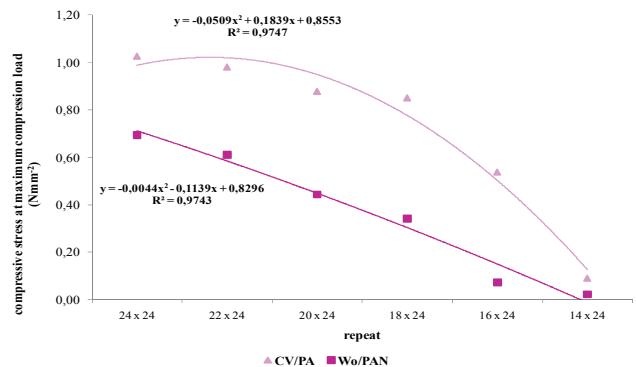


Figure 9. Compressive stress at maximum compression load for foldable zigzag knitted structures with different widths of zigzag ribs and constant number of courses in unit cell repeat

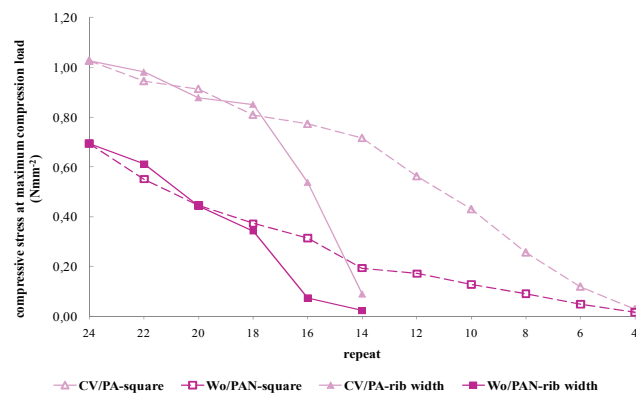


Figure 10. Comparison of compressive stress at maximum compression load for foldable zigzag knitted structures with various repeats: square – same number of courses and wales in repeat; rib width – different widths of zigzag ribs and constant number of courses in repeat

It can be seen from Tables 1 and 2 that the maximum compression load of CV/PA samples exceeded the maximum compression load of Wo/PAN samples for the structures with comparable repeats; as mentioned above, the knitted structures made from Wo/PAN yarn were thicker than the knitted structures made from CV/PA yarn (11). It can be concluded that the fibre and yarn type contribute substantially to the compression behaviour of samples as they were all knitted on the same machine and under the same conditions to eliminate the influence of the knitting process.

The maximum compression load decreased with the repeat reduction, which can be explained with the fabric thickness decrease. For all the measured repeats and materials, the maximum compression load at the compressed thickness of the knitted structure $t_{\text{comp}} = 1 \text{ mm}$ exceeded 100 N.

From the Tables 1 and 2, the compression properties of the foldable zigzag knitted structures compared to the selected actual compression materials can be seen. Bubble foil and rubber foam exhibit maximum compression load lower than 1000 N. The maximum compression load of the woollen felt exceeds substantially the maximum compression load of the other examined actual packaging materials. It reaches the highest value for the sample "felt 2" which has a very compact structure; its mass per unit area exceeds 1100 gcm^{-2} while its thickness exceeds 11 mm. The maximum compression load of the knitted samples with smaller repeats can be compared to the compressibility of the bubble foil and rubber foam. The maximum compression load of the knitted samples with bigger repeats can be compared to the compressibility of the woollen felt.

CV/PA foldable knitted structures with the repeat widths from 24 loops to 16 loops exhibit maximum compression load that exceeds the maximum compression load of the examined actual packaging materials except for the sample "felt 2". The compared actual packaging materials are thinner and have lower mass per unit area.

Figures 8 and 9 show that the decrease in compressive stress was not linear with the knitted structure repeat reduction. For the CV/PA knitted structures, the decrease got more distinctive with smaller repeats, whereas for the Wo/PAN knitted structures, the compressive stress decreased more in the case of bigger repeats. From the measurement results, the polynomial equations were found for each set of the knitted structure repeat. The equations are presented within the graphs in Figures 8 and 9. In the equations, x = the knitted structure repeat size and y = compressive stress at maximum compression load.

From Figure 10, it can be seen that the compressive stress decreased similarly for the structures with the repeat widths from 24 loops to 18 loops. The foldable knitted structures with the repeat widths smaller than 18 loops differed

substantially; the structures with the square repeat which were all fully folded (first series of samples) exhibited a gradual compressive stress decrease, while for the structures designed with various widths of zigzag ribs (second series of samples), an instant drop of compressive stress was evident. These structures did not fully fold when the rib width was smaller than approximately 7 loops. For a folded knitted structure thickness reduction to 1 mm, rather high loads were required.

4. CONCLUSIONS

The maximum compression load of CV/PA foldable knitted structures exceeds the maximum compression load of Wo/PAN structures with comparable repeats, although the knitted structures made from Wo/PAN yarn are thicker than the comparable knitted structures made from CV/PA yarn. The maximum compression load and fabric thickness decrease with the repeat reduction.

The decrease in compressive stress is not linear with the knitted structure repeat reduction. The compressive stress decreases similarly for the structures with the repeat widths from 24 loops to 18 loops. For the foldable knitted structures with the repeat widths smaller than 18 loops, compressive stress differs substantially; the structures with square repeat exhibit a gradual compressive stress decrease while for the structures designed with various widths of zigzag ribs, an instant drop of compressive stress is evident.

The maximum compression load of the knitted samples with smaller repeats can be compared to the compressibility of the bubble foil and rubber foam. The maximum compression load of the knitted samples with bigger repeats can be compared to the compressibility of the woollen felt.

Foldable knitted structures are compressible. To compress the examined foldable knitted structures to the thickness of 1mm, substantial loads are required. They can be appropriate for use in the clothing sector, interior design, in the automotive industry, for mattresses, and for the packaging and mechanical damage protection material.

NOTE

Parts of the research results were presented at the following conferences:

BLAGA, M., PAVKO-CUDEN, A., RANT, D., CIOBANU, R. Compressibility of foldable weft knitted structures with auxetic potential. 6th TEXTTEH International Conference, Bucharest, Romania, 17–18 October 2013.

PAVKO-CUDEN, A., BLAGA, M., RANT, D., CIOBANU, R. Compressibility of foldable weft knitted structures with auxetic potential. In: 13th International Izmir Textile and Apparel Symposium, Izmir, Turkey, 2–5 April 2014.

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