Study of thermal resistance of non-woven heat-insulating building materials

L Lisienkova\textsuperscript{1*}, L Komarova\textsuperscript{2}, and L Nosova\textsuperscript{3}

\textsuperscript{1}Moscow State University of Civil Engineering (National Research University), 129337, Moscow, Russia
\textsuperscript{2}Moscow Polytechnic University, 107023, Moscow, Russia
\textsuperscript{3}South Ural State Humanitarian and Pedagogical University, 454080, Chelyabinsk, Russia

E-mail: lisienkovaln@mail.ru

Abstract. The article presents the results of experimental studies of thermal resistance of non-woven heat-insulating materials under cyclic compression. It has been experimentally established that a change in the thickness of materials during cyclic compression leads to a change in the thermal resistance of studied objects. The dynamics and magnitude of the change in thermal resistance primarily depend on the structure, fibre composition and method of producing the material, to a lesser extent they depend on the initial thickness of the material before compression. As a result, a methodology for evaluation the thermal resistance of heat-insulating materials has been developed. The application of developed methodology allows objective selection of non-woven heat-insulating materials at the design stages of building construction.

1. Introduction
To provide thermal insulation of building, non-woven materials have been widely used lately [1, 2]. In the processes of its production and operation, non-woven materials undergo cyclic loads of low magnitude (1-20\% of the breaking load) that change its size and shape. The deformation of non-woven materials under compression significantly affects the thermal resistance properties of building objects. Unlike other materials, the properties of heat-insulating non-woven materials under compression are not well studied. The main disadvantage of the used methods for studying the properties of non-woven materials is that they do not predict changes in the thermal resistance for different stages of material life cycle.

The change in the thermophysical (heat-insulating) properties of non-woven materials in the processes of its production and operation is mainly caused by changes in their thickness when they are exposed to external compressive forces [3].

Thermal conductivity of building structures is provided heat-insulating properties of materials which are used as cushioning layer while the ability of materials to provide heat-insulation is determined by thermal resistance and a number of other properties.

Effective use of modern non-woven heat-insulating materials in building constructions suffers from the lack of objective methods for studying the patterns of changes in the thermophysical properties of materials under the influence of production and operation factors.
The development of objective methods for studying the thermal resistance of non-woven heat-insulating materials seems to be relevant as well as have scientific and practical use.

The purpose of the work is an experimental study of changes in the thermal resistance of non-woven materials under cyclic compression.

The objectives of this study include:
- material testing under cyclic compression;
- thermal resistance evaluation of tested materials after cyclic compression.

2. Materials
Over the past twenty years, new types of non-woven heat-insulating materials based on synthetic fibres have appeared [1-8]. Modern non-woven materials consist of the thinnest microfibers, which are 50–70 times thinner than a human hair (diameter of such fibres vary from 2 to 10 microns) and are able to effectively retain heat in a very small volume [2, 3].

Depending on the purpose, non-woven fabrics are divided into agriculture textiles, geotextiles, industrial, construction, medical, protective, filtering and absorbing, sanitary-hygienic, insulation, package, industrial [3].

Thermal insulation of non-woven materials depends on the density of the materials per its volume. Heat-insulating non-woven materials undergo compressive forces at all stages of its life cycle (production, storage, transportation, operation). This leads to material compression and thickness decrease, as well as decrease in the heat-insulation properties [9-12].

The pressure values at which the deterioration of the mechanical properties of textile fibers begins during compression in the pulp are the following ones: cotton fibers – 981·10² MPa, for viscose fibers – 1 470·10² MPa, for wool and polyester fibers – 1 962·10² MPa, for nylon fibers - 14 715·10² MPa [15]. In most cases, the amount of compressive forces in the production and operation of heat-insulating non-woven materials is not more than 5–20% of the destructive forces.

It is obvious that the compressive effects can lead to the accumulation of residual deformation in the material and a change in its thickness. According to several works [13-15], the most intense change in thickness in high-volume fibrous materials occurs in the range of values of pressure from 0 to 1.0 kPa.

Literature research has shown than in the scientific and technical literature, there is a lack of information about studies of the properties of non-woven materials under compressive forces. The majority of such researches ([9, 17-20]) are dedicated to the properties of non-woven fabrics for domestic use.

Bulk density and thickness are considered as the main factors while evaluating the quality of heat-insulating materials [10, 16]. The main thermophysical characteristics of such materials are: thermal conductivity and total thermal resistance. To preserve the initial values of thermophysical characteristics, materials should have high elastic properties under compression. In a work by Bessonova [18] it has been experimentally established that under the pressure forces thermal resistance decrease and the average density of some non-woven materials, on the contrary, increase.

Underestimation of external pressure force impact on materials leads to an inadequate evaluation of the real heat-insulating ability of building constructions during their exploitation. Therefore, when designing constructions it is necessary to take into account changes in the structure and properties of heat-insulating materials during compression that can occur while exploitation.

As research objects for this study heat-insulating non-woven fabrics of different composition, structure and production method have been selected; their characteristics are presented in Table 1.

Sample preparation, their shape and size selection as well as test design have been carried out in accordance with current regulatory documents: GOST 13587 “Non-woven fabrics and non-woven items. Acceptance rules and sampling method”, GOST 10681 “Climatic conditions for testing of samples and methods for their determination”.

The relative error of the test results with a repetition on 6-8 samples varied from 3 to 12% with a reliability of 95%; coefficient of variation is 10%.
Table 1. Characteristics of research objects.

| №  | Name material                        | Production method | Thickness, mm | Fiber composition, % | Surface density, g/m² | Bulk density, g/cm³ | Length, cm |
|----|-------------------------------------|-------------------|---------------|----------------------|-----------------------|---------------------|------------|
| 1  | Non-woven canvas (article 927622)   | Canvas            | 4.8           | Cotton - 50, Viscose - 50 | 250                   | 0.068               | 150        |
|    | Russia, GOST 14253                   |                   |               |                      |                       |                     |            |
| 2  | Non-woven cloth "Sherstipon" (Russia) | Combined          | 14.9          | Polyester - 40, Wool - 60 | 300                   | 0.020               | 300        |
| 3  | Non-woven cloth "Tinsulate" (modification P 150) Russia | Thermally glued | 15.8          | Polyester - 100     | 200                   | 0.012               | 100        |
| 4  | Non-woven cloth "Sintepon" (SK150/300) Russia | Thermally glued | 7.8           | Polyester - 100     | 140                   | 0.017               | 130        |

3. Methods
The deformation of non-woven fabrics during cyclic compression is associated with a change of the relations of structural elements of materials. Changes in the structure of materials lead primarily to a change in their geometric properties (shape, size, length, thickness).

3.1. Methods of studying the geometric characteristics of materials
Evaluation of structure and geometric properties of non-woven fabrics has been carried out with standard methods which are presented in table 2.
### Table 2. Normative documents used in research.

| № | Research stage         | Name of a document                                      | Document designation                                      |
|---|------------------------|--------------------------------------------------------|----------------------------------------------------------|
| 1 | Sample selection       | Non-woven clothes. Structural characterization methods  | GOST 15902.2-2003 (ISO 9073-2: 1995)                     |
| 2 | Sample preparation     | Non-woven clothes. Structural characterization methods  | GOST 15902.2-2003 (ISO 9073-2: 1995)                     |
| 3 | Thickness              | Textile materials. Canvases. Thickness evaluation methods | GOST 12023-93 (ISO 5084-77)                              |
| 4 | Linear density         | Non-woven clothes. Structural characterization methods  | GOST 15902.2-2003 (ISO 9073-2: 1995)                     |
| 5 | Surface density        | Non-woven clothes. Structural characterization methods  | GOST 15902.2-2003 (ISO 9073-2: 1995)                     |
| 6 | Geometric characteristics: length, width | Textile materials. Fabrics, non-woven fabrics and cloth items. Methods for determining linear dimensions, linear and surface densities | GOST 3811-72 |

3.2. Method for testing materials under cyclic compression

Sample tests under cyclic compression have been carried out on the device developed specially for cyclic compression [21, 22]. Schematic diagram of device implementation for cyclic compression is shown in Figure 1.

Among key features of non-woven heat-insulating materials their unevenness in thickness is outlined, what makes it difficult to distribute pressure force evenly over the sample area during testing. This disadvantage is eliminated due to the constructive solution of the device working body - indenter. The design of the indenter allows distribution of even pressure force on the material surface with uneven thickness.

Preliminary experiments made it possible to establish optimal parameters and conditions for the cyclic compression of the materials under study. Samples of the tested materials have undergone cyclic compression under the following conditions:

- indenter diameter, $D = 30$ mm,
- sample material diameter, $d = 25$ mm,
- time of compression and rest of the material for each cycle was 5 seconds per each operation;
- sample compression force = 15 daN,
- pressure on the sample with a diameter of $d = 25$ mm amounted to 0.30 kPa,
- number of cycles "load - unloading - rest" increased by 100 cycles with each next test from 100 to 400.

The thickness of studied samples after cyclic compression in laboratory conditions has been determined by a non-contact method using differential photo sensors of the instrument’s measuring system [21].
3.3. Method for evaluation of the main compression characteristics

The complete deformation of materials is determined by measuring the thickness of the sample before compression, during compression, and after compression. The formula for sample thickness before compression is:

\[ \delta_0 = H - h_0, \]  

where \( H \) is the depth of the device for placing the sample, \( h_0 \) is the distance of measurer position change when measuring the position of the sample before compression, mm.

Sample thickness under compression is calculated as:

\[ \delta_{\text{compr}} = N - h_{\text{max}}, \]  

where \( h_{\text{max}} \) is the distance of indenter position change during compression of the sample, mm.

Formula for sample thickness after compression is:

\[ \delta_1 = H - h_1, \]  

where \( h_1 \) is the distance of measurer position change after sample compression, mm.

The pressure on the sample is carried out by an external load of 0.01–4.0 daN, transmitted through an indenter with diameter of 10–30 mm. In test with material thickness of 0.1–20 mm diameter of the sample \( (d_1) \) for constrained compression conditions should be 30 mm, for free compression \( (d_2) \) diameter should be less than 25 mm. Optimal compression parameters have been experimentally established: indenter dimensions are 30 mm each, samples diameter is 15–30 mm; cycle of sample load and rest varies from 5 to 30 seconds, pressure on the sample lies in interval 0.01–3.0 kPa. While testing materials with thickness of 0.1–20.0 mm the relative random error was 3–12% at a 10%-level of significance with 10 tests.

3.4. Method for determining thermal resistance

Thermal resistance of the tested materials after cyclic compression was determined by two methods.

The first method: calculation of thermal resistance of materials in accordance with building regulatory standard of the Russian Federation «SNiP №23-02-02-2003 “Thermal insulation of buildings”» with the following formula:

\[ R = \frac{h}{\lambda}, \]  

where \( \lambda \) is the effective coefficient of thermal conductivity of the material, W/(m K), \( h \) is the thickness of the material, m.

The second method: an experimental evaluation of total thermal resistance of non-woven materials on the “PTS-225” device in accordance with technical state standard «GOST 20489–75 “Materials for clothing. The method of total thermal resistance valuation”».

Previous studies have established that thermal conductivity coefficient of non-woven heat-insulating materials for different purposes varies in the range 0.033-0.070 W/(ml) [18, 19].

![Figure 1. Device for implementing free (a), constrained (b) compression.](image)
4. Results
The results of evaluating thickness changes of materials after cyclic compression on the “PTS-225” device are presented in Table 3 [21].

**Table 3. Results of material thickness changes after cyclic compression.**

| №  | Material sample                        | thickness $h$, mm | thickness change after 400 compression cycles, $\%$, $A = \frac{L_0 - L_n}{L_0} \times 100$ |
|----|----------------------------------------|-------------------|-----------------------------------------------------------------------------------|
| 1  | Non-woven canvas (article 927622)      | 4.80              | 3.97 3.66 3.41 3.33 30.6                                                          |
| 2  | Non-woven cloth “Sherstipon”           | 14.9              | 12.60 11.46 10.83 10.80 27.5                                                        |
| 3  | Non-woven cloth “Sintepon” (SK150/300) | 7.80              | 6.40 6.22 6.0 5.7 26.9                                                           |
| 4  | Non-woven cloth “Tinsulate” (P 150)    | 15.80             | 13.60 13.18 12.50 12.48 21.0                                                        |

Results presented above (table 3) were used for material thermal resistance evaluation as well as PTS-225 device and calculation method according to formula (4). Thermophysical properties are presented in table 4.
Table 4. Thermophysical properties of materials after cyclic compression.

| №  | Material                              | Thermal resistance, m²K/W |
|----|---------------------------------------|--------------------------|
|    |                                       | number of compression cycles, n |
|    |                                       | 0  | 100 | 200 | 300 | 400 |
|    |                                       | 0  | 100 | 200 | 300 | 400 |
| 1  | Non-woven canvas (article 927622)     | 0.143 | 0.115 | 0.104 | 0.099 | 0.096 |
| 2  | Non-woven cloth "Sherstipon"          | 0.285 | 0.241 | 0.220 | 0.208 | 0.208 |
| 3  | Non-woven cloth "Sintepon" (SK150/300)| 0.199 | 0.163 | 0.160 | 0.155 | 0.155 |
| 4  | Non-woven cloth "Tinsulate" (P 150)   | 0.303 | 0.261 | 0.253 | 0.240 | 0.237 |
|    |                                       | 0.119 | 0.100 | 0.090 | 0.083 | 0.083 |
| 1  |                                       | 0.314 | 0.266 | 0.240 | 0.228 | 0.220 |
| 2  |                                       | 0.153 | 0.140 | 0.133 | 0.128 | 0.125 |
| 4  |                                       | 0.294 | 0.240 | 0.240 | 0.238 | 0.234 |

Data in table 4 show that the biggest change in thermal resistance after 400 compression cycles (27–32%) can be seen for samples of material 1, 2 — non-woven fabric (article 927622) and "Sherstipon". In thermally bonded samples of materials 3, 4 (synthetic "Sintepon" and "Tinsulate"), the thermal resistance after 400 compression cycles has changed much less (no more than 18–22%).

5. Discussion
The results of thermal resistance evaluation of heat-insulating materials are graphically illustrated in figure 2. Analysis of empirical dependences has shown that the largest change in the values of thermal resistance R (m²K/W) occurs after 100 cycles.

![Figure 2. Results of thermal resistance evaluation of heat-insulating materials (1 – “Tinsulate”, 2 – “Sherstipon”, 3 – “Sintepon”, 4 - non-woven canvas): —— on PTS-225 device, —— calculated by formula (4).](image)

It can be seen in figure 2 that after 100 compression cycles thermal resistance of samples of materials № 1-4 (Table 2) changed by 17.2%, 15.4%, 13.9% and 17.9%, respectively. After 400
compression cycles, thermal resistance of material samples №1-4 (Table 2) changed by 30.6%, 27.5%, 21.0% and 26.9%, respectively.

The smallest change in thermal resistance after 400 compression cycles can be observed for samples of materials № 3 and 4 (Table 2). Such small change is due to the fibrous composition, density and high porosity of these materials.

A comparative analysis of the data presented in figure 2 has showed the consistency of the results of evaluation thermal resistance on PTS-225 device and by calculation with formula (4). The relative error between the results gained by two methods was not more than 10-21%.

Moreover, analysis of experimental data has proved that a decrease in the material thickness leads to a decrease in their thermal resistance properties. Underestimation of this effect (thickness change) leads to an inadequate evaluation of the real heat-insulating ability of building constructions during their exploitation.

In order to provide sufficient level of thermal resistance, heat-insulating fibrous materials for building structures should have relatively high elastic properties during compression. Potential compressive forces that can affect building and material it is made of should be taken into account while designing structures. It will provide a rational choice of heat-insulating materials at the design stage of building projects.

6. Conclusion
To sum up the study, the following results have been outlined. The patterns of changes in thermal resistance of non-woven heat-insulating materials under cyclic compression have been investigated. It was experimentally established that a change in the thickness of the studied materials after 400 compression cycles leads to loss of thermal resistance properties of 20-32%. The magnitude and dynamics of changes in thermal resistance depend on the conditions and parameters of the test as well as on the composition, structure and method of producing materials.

A comparative analysis of the experimental data has proved the consistency of the results of evaluation of thermal resistance on the PTS-225 device and by calculation on suggested formula, the relative error between the results varies from 10 to 21%.

The research results have illustrated the possibility of applying the cyclic compression method to evaluate the thermal resistance of non-woven heat-insulating building materials.

References
[1] Mukhamedzhanov G 2013 Rossijskij rynok netkanyh uteplitelej. Sostoyanie, problemy perspektivy (in Russian) Rabochaya odezhda 1 pp 6-8
[2] Shafiqul I, Gajanan B 2019 Environmentally-friendly thermal and acoustic insulation materials from recycled textiles Journal of Environmental Management 251 109536
[3] Wilhelm A, Fuchs H and Kittelmann W 2006 Nonwoven fabrics: raw materials, manufacture, applications, characteristics, testing processes (Germany: John Wiley & Sons) p 775
[4] Hanisch V, Kolkmann A, Roye A and Gries T 2006 Influence of machine settings on mechanical performance of yarn and textile structures ICTRC 2006 1st International RILEM Symposium on Textile Reinforced Concrete (conference proceedings)
[5] Hanisch V, Kolkmann A, Roye A and Gries T 2006 Yarn and textile structures for concrete reinforcements (Bangkok: FERRO8)
[6] Xiaonan H, Acar M and Silberschmidt V 2011 Non-uniformity of deformation in low-density thermally point bonded non-woven material: effect of microstructure Journal of Materials Science 46.2 pp 307-15
[7] Rumyantsev B, Zhukov A 2012 Principy sozdaniya novyh stroitel'nyh materialov (in Russian) Internet-vestnik VolgGASU 3(23) p 19
[8] Mukhamedzhanov G 2013 Netkanye teploizolyacionnye stroitel'nye materialy i izdeliya (in Russian) Polimernye materialy pp 26-29
[9] Hannong R Stretchable nonwoven materials with controlled retraction force and methods of
making same U.S. Patent Application 10/647,008

[10] Kemal C and Yüksel B 2004 Environmental impact of thermal insulation thickness in buildings Applied Thermal Engineering 24.5-6 pp 933-40

[11] Das D and Behnam P 2014 Composite nonwoven materials: structure, properties and applications (UK: Elsevier) p 225

[12] Wazna E, Fatih M, Abdelsam M and Cherkaoui E, 2017 Thermophysical characterization of sustainable insulation materials made from textile waste Journal of Building Engineering 12 pp 196-201

[13] Sakthivel S and Ramachandran T 2012 Thermal conductivity of non-woven materials using reclaimed fibres International Journal of Engineering Research and Applications (IJERA) 2.3 2986

[14] Sabetzadeh N 2012 Thermal conductivity of polyacrylonitrile nanofibre web in various nanofibre diameters and surface densities Micro & Nano Letters 7.7 pp 662-66

[15] Vajnsheinker V, Berndshetm M 1970 Vliyanie toshchiny i dliny himicheskih volokon i metoda ih formirovaniya na svojstva igloprobivnyh netkanych materialov (in Russian) Tekstil'naya promyshlennost 9 pp 3–10

[16] Treshchalina A, Tyumenev Y and Treshchalin M 2007 Opredelenie effektivnogo koefficienta teploprovodnosti netkanogo materiala (in Russian) Izvestiya VUZov. Tekhnologiya tekstil'noj promyshlennosti 4 pp 11-14

[17] Balyasov P 1975 Szhatie tekstil'nyh volokon v masse i tehnologiya tekstil'noj proizvodstva (in Russian) (Moscow: Legkaya industriya) p176

[18] Bessonova N 2007 Teplofizicheskie svojstva materialov dlya izdelij legkoj promyshlennosti (in Russian) (Moscow: Izd-vo IIC MGUDT) p 118

[19] ZHiharev A Razvitie nauchnyh osnov i razrabotka metodov ocenki kachestva netkanych materialov (in Russian) (Moscow: MGUDT) p 374

[20] Deryabina A, Lisienkova L, Trofimov E and Myazina Y 2001 Creped nonwoven materials National Research University – South Ural State University Patent Buro RU 144579 U1

[21] Lisienkova L, Volkova E, Nosova L and Baranova E 2020 A method of the study of deformation of non-woven heat-insulating building materials Advances in Intelligent Systems and Computing 982 pp 709-22