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Brief Report

Influences of a Variety of Reinforcements on the Durability of Reinforced Bitumen Sheets Operating at Variable Temperatures

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Abstract: This manuscript provides an overview of the most commonly-produced bitumen roofing sheets, focusing on the types of reinforcements used for their production and the reinforcements' effects on the durability of tensile mechanical properties of roofing sheets under thermal loads. The paper includes the analysis of working conditions of roof coverings in the mid-European transitional climate, i.e., exposed to temperatures passing through 0 °C for three seasons in a year, periodic exposure to negative temperatures reaching −15 °C and positive temperatures up to +70 °C, justifying the above-mentioned emphasis on thermal load. It draws attention to technical problems related to the cooperation of roofing sheets with roofing substrates, with particular emphasis on concrete substrates. For the purposes of the work, the analyses were carried out with regard to the assessment of the service life of roof coverings made of various reinforcements working in conditions of variable temperatures and thus exposed to the transfer of thermal movements of substrate plates. The analyses also included the impact of different coefficients of thermal expansion of the materials in contact with other materials within roof coverings on the incidence of damage to cover layers. Particular attention was paid to the conditions resulting from the production process of roofing sheets effect on the durability of roof coverings made of these materials. Additionally, there were set directions for further work to calculate the impact of stresses, arising in layers of roof coverings during their operation in changeable negative and positive temperatures, on the incidence of mechanical damage to these coverings.

Keywords: reinforced bitumen sheets; durability of sheet coverings; variable operating temperatures; variety of reinforcements

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1. Introduction

Roof coverings made of reinforced bitumen sheets are used in small- and large-cubature buildings. These coverings have been used for many years and over the last few decades they have undergone a complete evolution.

Reinforced bitumen sheet is a factory-made flexible sheet, including any carriers/reinforcements, facings, surface texture and/or backing. The top surface is covered by a finishing layer which protects the sheet against weathering, for example, fine or coarse mineral granules. The underside is protected by an anti-sticking substance for transport and/or storage purposes. Bitumen sheets are supplied in roll-form ready for use. The reinforcement plays one of the key roles in the structure of roofing bitumen sheet, since it provides at least 90% of tensile strength of the finished products [1–3]. manufacturers must ensure the stability of bitumen sheets, and especially their tensile mechanical properties.

Coatings are used to create a tight and continuous waterproofing layer on the reinforcement, thanks to which it has no direct contact with the external environment. Absorbent reinforcements (cardboard or non-woven fabric) are impregnated with asphalts with a low softening point prior to the application of the coating mass. During the manufacturing process, the reinforcement is highly stretched, which, in the case of tension-prone materials, contributes to the development of unwanted stresses within the membrane, which are then stabilised in the final product by the cooled coating compound. This phenomenon becomes apparent after such a membrane has been incorporated into the roofing, when the coating compound softens after being heated by the sun on hot days. This allows the reinforcement to relax, and consequently, for the longitudinal shrinkage of the laid membrane strips, which is particularly visible in transverse overlaps [2,4,5].

It should also be noted that, despite the similar geometrical and material properties of the reinforcements, their mechanical properties are very much dependent on the microstructure and direction of the reinforcing fibres [6].

The main component of coating masses is bitumen supplemented with the addition of fillers and modifiers. Initially, tar as well was used to produce coating masses. In the 1980s, the use of tar [7] was discontinued due to its carcinogenic effect, and modified bitumen additives were introduced on a large scale to improve the rheological properties of coatings. These techniques have been continued to this day. Modifications of coatings [8,9] have been successively introduced, extending their viscoelasticity, which in turn has resulted in increases in the temperature-resistance of finished products, both for high and low temperatures. The modifications primarily use SBS [10–12], i.e., styrene–butadiene–styrene, obtained in the process of copolymerisation of styrene and butadiene, increasing the range of viscoelasticity of coating masses in temperatures from −15 °C to +110 °C. At ambient temperature, two phases are formed in the bitumen mixture with the SBS copolymer:

- Macro polymers saturated with low-molecular components of bitumen (paraffins, maltenes); and
- "Bitumen" rich in asphaltenes, practically free of polymers.

The polymer phase consists of saturated polybutadiene microphase and pure polystyrene. This composition allows for achieving a cross-linked three-dimensional structure, thanks to which the composites act similarly to thermoplastic rubbers, showing similar elasticity, i.e., a practically complete elastic recovery after deformation [13,14]. The effects of the coatings on the final properties of the material depends on the percentage content of these additives. For modified bitumen roofing sheets, the percentage content of SBS in relation to bitumen is within the range of 10–15%, but attempts have been made to increase this additive up to 30%. An increase in the modifier content of up to 30% leads to significant increases in the costs of finished products, and therefore this solution has not found wide interest among producers. On the other hand, a 5–7% additive level of SBS is commonly used to produce so-called "low-modified" roofing sheets.

In mid-European transitional climatic conditions, i.e., in Poland, the second modifier, i.e., APP (atactic polypropylene), an amorphous substance obtained as a by-product in the process of propylene polymerisation, is used less frequently. When mixed with bitumen, APP penetrates deeply into the maltene phase, creating a stabilised network and dispersing asphaltenes [2,13]. The addition of this ingredient increases the viscoelastic range of coatings within the temperature range of −5 °C to +130 °C and is therefore more useful in hot climates. Polymers from the polyolefins group (PO) are used as modifiers in bitumen masses, as well. These polymers are primarily manufactured to produce modified bitumen. Such modified bitumen is used for the construction of roofs or roads. The strength of the mechanical parameters and the quality of bitumen mass made of PO are both higher [15].

As mentioned above, the bitumen used for roofing applications is, as a standard practice, modified by polymers. Austrian scientists [16] proposed to re-use recycled polymer during the production of polymer-modified bitumen (PmB), reducing the amount of polymeric waste. The cited research results confirmed that recycling processes may degrade or contaminate polymers, leading to reduced crystallinity and lower melting temperatures.

Such changes may even be taken as beneficial, resulting in improved mixing behaviours and a more homogeneous distribution of the polymer within the bitumen.

The search for methods to increase the viscoelasticity range of roofing sheet coating masses is accompanied by works on modifying the textures of the undersides of roofing sheets, efforts aimed at widening the functionality of finished products used as ventilation layers [2]. The underside of roofing sheet features strip-profiled channels, which, together with the properly selected composition of coating mass (bitumen-resin or bitumen-sand), after gluing strips to the substrate, enable the distribution of gases under the waterproofing layer. These solutions are mainly used in roof coverings, but they can also be effective for repairs of damp horizontal insulation of ceilings located directly above rooms in underground parts of buildings. These methods of preparing the underside of roofing sheet strips allow for the gluing of them to the substrate in strips, leaving ventilation ducts unglued and under the surface of previously made layers. Depending on the method used to modify coating masses within ventilation ducts, gluing processes consist of either hot-air welding or thermal activation of the bitumen adhesive applied in strips. In the process of this activation, which takes place at up to 1000 °C, coating masses applied on the underlay or intermediate layers of roofing sheet strips do not melt and bitumen does not liquefy, but they both stick to the area of profiled ridges. For several years, manufacturers have been increasing the thickness of roofing sheets, offering single-layer solutions instead of multi-layer ones, which requires applying several layers of roofing sheet (at least two) within installed waterproofing systems. In addition to lower costs, in comparison to multi-layer systems, single-layer roofing reduces the emissions of harmful gases generated in the process of gluing.

Roofing sheets are used for waterproofing roof coverings and insulating terraces and balconies, as well as waterproofing underground parts of buildings [1,2]. In each of the above areas, the scope of their operation depends on the operational loads that affect them. The effects of these actions are different in different parts of buildings and structures, and each of the mentioned areas, due to their operational specificity, should be considered individually. For many years, attempts have been made to assess the durability of the mechanical properties of roofing sheets under tension [6,17]. Article [6] analyses the mechanism of damage to roofing sheets under tension in different directions to the point of breakage. Article [18] assesses the effect of the relative stiffness of a roofing sheet reinforcing insert on the type of damage that it causes, in both single- and multi-layer systems.

The durability of roofing sheet coverings has a considerable impact on the durability of buildings, since most processes that destroy the substance of buildings occur in the presence of water and moisture. For this reason, it is vital to ensure the longest possible period of failure-free operation of roofing materials. Monitoring of roof coverings and proper diagnostics of their damage is a key issue from the point of view of all users of buildings [19]. However, to meet this requirement, it is necessary to know the processes that significantly affect the proper selection of roofing solutions for specific service loads.

Although the possible destruction of the roof covering at the time of its creation is not a construction disaster, its destructive character lasting for a long time may consequently lead to a failure or a construction disaster [20].

Roofing sheets can be laid on rigid substrates, i.e., concrete and cement plaster, as well as on flexible substrates, for instance, ones made of thermal insulation materials. This manuscript focuses on the durability analysis of one of the applications, i.e., roof coverings made of bitumen sheets welded to the substrate using propane-butane gas torches, and laid on rigid substrates. Such solutions are encountered in the following cases:

- In non-ventilated flat roofs when the covering is laid on additional layer made of cement mortar, which separates the thermal insulation from the roofing layer;
- In ventilated flat roofs when the thermal insulation is laid on the ceiling above the top storey and the roof covering lies on top of the roof situated above the air void made above this thermal insulation.

The purpose of these analyses is to draw attention to usefulness of making the appropriate selection of roofing sheet types for specific substrates, with special attention paid to the material's ability to carry service loads by the reinforcements of bitumen sheets. This manuscript attempts to clarify whether the movements of the substrate slabs caused by temperature changes have an effect on the breaks in the reinforcements of bitumen sheets bonded to these substrates, and which types of reinforcements best transmit such interactions.

2. Analysis of Failure Characteristics of Reinforced Bitumen Sheets under Service Loads—Discussion of the Problem

2.1. Analysis of the Effect of Bitumen Covering on the Durability of Bitumen Roofing Sheets

In this section, the effect of the tape of bitumen coating on the occurrence of mechanical damage to the entire section of the roofing bitumen sheet during use under natural conditions is analysed. In the bitumen sheet, the thickness of the bitumen compound is small, up to a maximum of 5 mm, and it protects the surface of the layer against ageing factors associated with the surface effects of varying positive and negative temperatures, and UV effects in the presence of water and moisture. According to the literature, the influence of bitumen coating on the transfer of tensile stresses acting on the substrate side is small [3]. In the case of bitumen, when a constant amplitude of stress is applied, the crack-propagation time of the specimen is short, so the end of the test is strictly defined by the rupture of the bitumen film. During fatigue testing of viscoelastic materials, the value of the modulus of stiffness changes due to the occurrence of creep or relaxation. The reason for these changes is the heating of the specimen during the test. As the mechanical properties of bitumen change significantly as a function of temperature, fatigue tests should be conducted at a minimum of two temperatures. As a result of the above-mentioned factors, in most cases a parallel Wohler fatigue curve is not observed for bitumen in the stress σ, log N system, or for a larger number of fatigue cycles N. Fatigue tests on bitumen are usually carried out using a viscometer to apply a sinusoidally varying stress with a constant amplitude [21].

The available technical literature mainly discusses the results of tests on bitumen sheets subjected to accelerated ageing under laboratory conditions involving both high and low temperatures with simultaneous exposure to UV radiation, water and moisture, although changes in physical and chemical properties due to accelerated weathering might not directly correlate to those occurring naturally [12]. Heat aging has been reported to be effective in evaluating the performance of modified bituminous membrane [22] and simulating the effects of natural aging [23]. For example, Puterman et al. [24] measured the tensile properties, cold flex temperature and the water-pressure resistance of various types of roofing membrane which were naturally exposed under normal service conditions and showed that SBS-modified membranes retained better low-temperature flexibility than did the APP-modified membranes, after comparable periods of exposure under similar service conditions. Data on the SBS- and APP-modified membranes showed that the exposure hardly affected the properties determined by the reinforcement but had a strong effect on the properties that are governed by the bitumen/polymer material. They reported that the cold flex temperature of an SBS-modified bituminous membrane increased by about 12 °C after five years of natural exposure, but the tensile strength and elongation were hardly affected. The data also showed that SBS-modified membranes retained better low-temperature flexibility than did the APP-modified membranes, after comparable periods of exposure under similar service conditions. Baxter et al. [25] showed that the tensile strength of five SBS-modified bituminous membranes increased and the cold flex temperature of two SBS-modified bituminous membranes rose by about 15 °C after heat aging at 80 °C for 28 days. Rodriguez et al. [26] studied the effects of heat aging and test temperature on the tensile strength and elongation of two APP-modified and two SBS-modified bituminous membranes. For the two SBS-modified membranes, heat aging (80 °C for 168 days) did not significantly affect the tensile strength at 23 °C but it reduced the elongation by 20–40%.

However, heat aging reduced the tensile strength of these membranes at –30 °C by about 20% and increased the elongation by about 60–330%. The results of these studies are mainly related to the modification of bitumem coverings of the sheets [27,28] and not to the influence of ageing factors on the reinforcements. Liu et al. [12] showed that heat aging affected matrix-controlled properties such as elongation and strain energy but hardly affected the reinforcement-controlled properties such as breaking strength.

Although accelerated testing can be useful in ranking different materials, it has many shortcomings [29] without giving an answer as to how these bitumen sheets will behave under service conditions as a result of their interaction with the substrate.

A major problem with roofing bitumen sheets is damage to the coating compound during welding, which leads to a loss of bitumen viscosity and deformation of the roofing sheet, as shown in Figure 1.

Figure 1. Roofing sheets damaged during the welding of the cover.

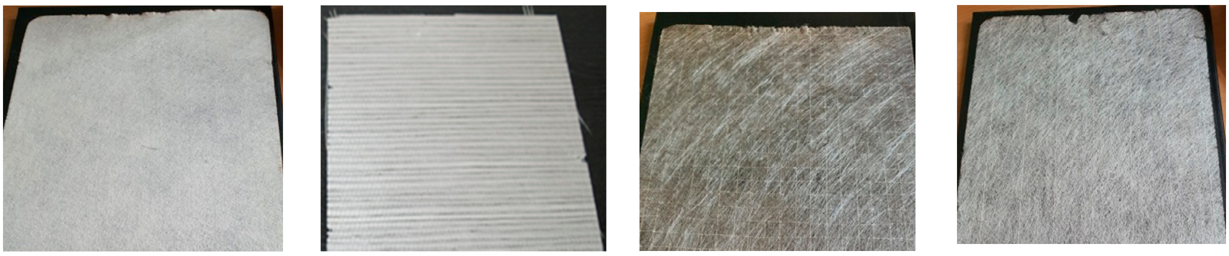
2.2. Analysis of the Effect of Roofing Reinforcements on Mechanical Properties of Roofing Sheets

The main component of a roofing sheet that transfers deformations in a structure is its reinforcement, and from this point of view the mechanical strength of the latter is critical [1,2]. Based on market analysis carried out for the leading European roofing sheet manufacturers, a study compared how this characteristic changed in different products by setting the limit values of roofing sheet tensile strength as a function of the type and mass per unit area of the reinforcement used. The values are summarised in Table 1. The literature reports showed a clear difference in the mechanical response depending on the material and tested sample [6]. The quoted values of the tensile mechanical properties of the roofing sheet, i.e., maximum tensile force and elongation at maximum force, were determined based on the analysis of the records provided in the declaration of performance specified in roofing sheet tests according to the research methodology included in EN 12311-1:1999 [2,30], and carried out on strips 5 cm wide and 200 cm long, with a distance between measuring points of 100 mm and between jaws of 120 mm, under tension, and at a testing speed of 100 mm/min. The above analysis also showed that at present the most common groups of materials used to produce roofing reinforcements are polyester non-woven fabrics, glass fabrics, mixed polyester-glass fibres, and glass veil. For bitumen sheets, there are no requirements in the European standard EN 13,707 [31] for tensile properties, i.e., elongation and maximum tensile force, they should be in accordance with the values declared by the manufacturer, and with the declared tolerance. This lack of requirements has contributed to the fact that the values given in Table 1, determined on the basis of an analysis of the European market, are generally regarded in Poland as the requirements for bitumen sheets produced on the mentioned types of reinforcements.

Table 1. Summary of tensile mechanical properties of roofing sheets and mass per unit area of the most common roofing reinforcements [2].

Properties	Roofing Reinforcement			
	Polyester Non-Woven Fabric	**Glass Fabric**	**Mixed Polyester-Glass Fibres**	**Veil and/or Glass Fleece**
Mass per unit area of roofing reinforcement, g/m^2	≥180	≥200	≥160	≥60
Max. tensile force, N/50 mm:				
– longitudinal	≥800	≥900	≥600	≥300
– transverse	≥600	≥900	≥500	≥200
Elongation at max. tensile force, %				
– longitudinal	≥40	≥2	≥2	≥2
– transverse	≥40	≥2	≥2	≥2

All types of roofing sheets listed in Table 1 are used in roof coverings, with the underlay or intermediate layers of the roofing made of underlayment sheets, and the top layers of top-covering sheets, i.e., with the upper side of the strip protected against solar radiation, e.g., using coarse mineral roofing granules. The given summary shows that the production of sheet reinforcements uses materials with the following mass per unit area: polyester non-woven fabrics—at least 180 g/m^2, glass fabrics—min 200 g/m^2, glass veil also known as glass fleece—at least 60 g/m^2. Reinforcements made of mixed polyester-glass fibres with a mass per unit area of at least 160 g/m^2 are most often made of polyester non-woven fabric reinforced with glass threads. The images of the reinforcements mentioned are shown in Figure 2.



(**a**) (**b**) (**c**) (**d**)

Figure 2. Images of the various most common roofing reinforcements, respectively: (**a**) reinforcement of polyester non-woven fabric, (**b**) reinforcement of glass fabric, (**c**) reinforcement of polyester non-woven fabric with glass threads, and (**d**) glass veil.

By analysing the mechanical properties of roofing sheets under tension, it can be unquestionably stated that only roofing reinforcements of polyester non-woven fabric elongate at maximum tensile force (above 40%), simultaneously maintaining their high mechanical strength at least 600 N/50 mm (for transverse samples) and at least 800 N/50 mm (for longitudinal samples). Considering the above values, these roofing sheets can be used on roofs whose structures work within a large range of service loads, and even with concurrence of major deformations. This statement finds confirmation in structural tests which indicate the increased strength and durability of this group of products [6]. Admittedly, roofing reinforcements of glass fabric, due to the high values of maximum tensile forces, min. 900 N/50 mm, transfer even higher service loads occurring in roof coverings than do roofing reinforcements of polyester non-woven fabric, with, however, a much smaller range of deformations, i.e., at least 2%. The recorded maximum elongation values at maximum tensile force for roofing reinforcements of glass fabric usually do not exceed 5%. Roofing reinforcements of mixed polyester–glass and glass fleece are characterised by even lower strength parameters, in both cases with elongation values at maximum strength slightly exceeding 2%. Although, with these low elongations, roofing reinforcements of mixed polyester–glass are characterised by relatively high values of maximum tensile force: at least 500 N/50 mm (for transverse samples) and at least 600 N/50 mm (for longitudinal samples). In the case of roofing reinforcements of glass fleece, these values are two times lower: at least 200 N/50 mm and 300 N/50 mm. Considering the above, roofing reinforcements of glass veil, according to the present authors, can be used as one layer in multi-layer roof coverings and should not be folded onto the vertical planes of over-roof elements.

2.3. Service Loads Acting on Roofing Sheet Coverings

In roof coverings, roofing sheets are exposed to numerous actions, such as climatic factors—different negative and positive temperatures in the presence of precipitation and wind suction [32–35]. There are also actions related to snow removal from roofs and other maintenance and repair works that often cause mechanical damage from both static and dynamic loads [36]. These additional actions are difficult to predict and therefore cannot be classified as cyclic loads, which interferes with analysing this phenomenon as a function of durability. This manuscript focuses on assessing the effect of variable temperatures acting on roofing sheets in operating conditions, excluding the action of wind suction, which is such a broad phenomenon that it would require a separate analysis.

Roofs with a traditional layer system are subject to deformations due to temperature differences and uneven subsidence of buildings. Temperatures acting on roofing layers vary depending on the location of buildings and climate variability, including the action of solar radiation energy throughout the year, as well as the colour of topcoat layers. In an urbanized area, there is a phenomenon of "urban heat zone" consisting in a significant increase in temperatures inside urban centres in comparison to surrounding peripheral areas. The action can be equated to an island (or sometimes to an archipelago of islands) surrounded by an "ocean of relative coolness" [37]. This phenomenon occurs even in towns with a population not exceeding 3,500 inhabitants [37]. The key factor contributing to the heating of roof covering materials is solar energy. The action of solar energy on buildings depends on numerous elements, such as: architectural form, shading probability by neighbouring buildings, type of external surfaces and reflectivity of the environment. It should also be remembered that solar radiation is a source of energy with different values. The level of solar energy reaching the border of the atmosphere is only a small part of the calculation of energy emitted by the sun. This value is known as solar constant. As it passes through the atmosphere, the value of the solar constant decreases due to the processes of scattering and absorption. This change in the intensity of solar radiation causes fluctuations in the temperatures of the outside air. The relationship between solar radiation and air temperature was defined by Mackey and Wright as the solar value of outside air temperature. The hypothetical value of outside air temperature at which thermal power would be encountered by non-sunlit surfaces of outer partitions is equal to the thermal power encountered by sunlit partitions at a given value of outside air temperature, defined as solar temperature [38,39]. One of the formulas used to calculate solar temperature is presented below (1) [40].

$$t_{oe} = t_{ao} + R_{so} \cdot \alpha \cdot I_G \tag{1}$$

where:

t_{oe}—Solar temperature, °K;
t_{ao}—Outdoor air temperature, °K;
R_{so}—Heat transfer resistance on the outer surface, m^2K/W;
α—Coefficient of solar radiation absorption;

I_G—Total intensity of solar radiation, W/m^2.

Poland is located in the mid-European transitional climate, i.e., exposed to temperatures passing through 0 °C for three seasons in a year. The average air temperature in the summer of 2022 (June-August) in Poland was 19.3 °C, i.e., 1.3 °C higher than the multi-year average temperature value for that month (climatological normal period 1991–2020). The anomaly index, i.e., deviations from the multi-year monthly averages over the period 1991–2020, ranged from 1.0 °C to 2.0 °C [41].

In winter, roof coverings are exposed to negative temperatures. The anomaly rate in 2022, i.e., deviations from the long-term monthly averages from the period 1991–2020, ranged from −1.0 °C to 3.0 °C [42]. It was found that in the central and eastern part of Poland, extreme temperature values even drop below −17 °C. The layers of roof coverings made of bitumen roofing sheets may therefore be exposed to the extreme temperatures quoted above.

The studies on the correlation between ambient temperature and temperature measured on the surface of roofing conducted in North America [43] confirm that the colours of roofing membranes have a significant effect on the temperatures occurring at their surface. The maximum temperatures attainable on the surface of a black membrane can reach up to 70 °C in summertime, with an ambient temperatures of up to 24 °C. In winter, the values reach −20 °C at an ambient temperature of −15 °C. Studies conducted in the Czech Republic have confirmed the above observations and indicated that the colour of roofing granules on the roofing sheet surface has, in practical terms, a considerable effect on the surface temperature of bitumen sheets and thus, on their aging rate. From the selection of the colour range of roofing granules, light colours should be preferred to dark colours such as red. At the extreme, combined with the reflection of the sunlight, the temperature can exceed, in the long run, approx. 80 °C [44]. However, it cannot be denied that, in the climatic conditions of Europe, deviations from the above values are confirmed [45]. For example, in the northern Alps, for the purposes of testing waterproofing systems [46], minimum daily temperatures in winter were set at 0 °C and maximum average temperatures in summer at 18 °C, with an average 65 mm/month precipitation in winter and up to 150 mm/month in summer. At the above-mentioned outside temperatures, the temperature determined on the surface of the topcoat made of dark ceramic tiles reached 45–50 °C on sunny days.

Considering the above, the following maximum temperatures at the surface of roofing membranes can be assumed for assessing the change in mechanical properties of roofing products in a mid-European transitional climate:

- +70 °C in summer, with outside air temperatures of +24 °C;
- In winter, −15 °C at outside air temperatures of −20 °C.

2.4. The Effect of Variable Service Temperatures on the Durability of the Substrate—Roofing Sheet System

Roof coverings are laid on, among other surfaces, rigid substrates, i.e., reinforced concrete elements of flat roofs. The substrate and the roof covering are subject to mutual interactions, which may result in damage to the roofing sheet layers, longitudinal or transverse overlaps or joints at the roofing sheet-substrate interface. These situations can result from the differences in deformations in the cross-sections of roofing layers caused by temperature gradients, whether daily, seasonal, or annual, as determined for specific locations of buildings, and different for substrates and covering materials. In summer, deformations of roof coverings with the traditional arrangement of layers affect predominantly roof-supporting structures, whereas in winter—roof coverings, contributing to their cracking.

In Poland, the following temperature ranges are customarily adopted [47]:

- ΔT = 20 °C—Most common range of changes of day temperatures (in winter—from –5 °C to +15 °C, in summer—from +10 °C to +30 °C);
- ΔT = 40 °C—Frequent range of changes of daily and annual temperatures;
- ΔT = 70 °C—Maximum annual range of changes of temperatures occurring in Poland.

With reservation of the above, the extreme elongation of the concrete substrate (under the roofing sheet layer), assuming the maximum value of temperature gradient and linear expansion coefficient of concrete to be $\alpha_t = 1.0 \times 10^{-5}$ °C, is approx. 0.07%. This value is many times lower than the value of maximum elongation of roofing sheets with other types of reinforcements, such as those obtained, for instance, during tensile tests, as provided in Table 1. However, such a comparison may lead to erroneous conclusions, such as failing to consider the effects of the roofing sheet's production process affecting its performance properties and further, the specificity of work in the roof covering.

Roofing sheets are anisotropic materials. Therefore, the coefficient of linear expansion may also show anisotropy in this case. In addition, the value of the coefficient of linear expansion of a roofing sheet is the resultant stemming from the type of reinforcement used and the type of coating mass. Hence, it is difficult to determine it unequivocally. For example, the value for pure bitumen is assumed to be 1.9×10^{-4}/K. In addition, in the first summer season after the roof covering is completed, the effects of possible linear expansion of the roofing sheet resulting from the structure of raw materials used for its production are eliminated by reinforcement shrinkage due to relaxation after the bitumen mass' exposure to sunlight. These stresses are mainly found in the roofing sheets' polyester reinforcement, which tends to stretch during the manufacturing process, and this elongation is temporarily fixed by the cured coating mass, but only until it relaxes, which may occur after reheating the strip laid in the roofing material. When this is applied, the shrinkage of the roofing sheet can reach up to 0.5% of the strip length. In roofing sheets with glass reinforcement, this phenomenon usually does not occur. A different coefficient of thermal expansion of both contact materials, i.e., the concrete/cement mortar substrate and the roofing sheet, may be an additional reason for reducing the durability of roofing coverings during their operation.

Additionally, in accordance with good construction practices, in rigid substrate under roofing sheets (e.g., those made of cement concrete), thermal expansion joints are made, the purpose of which is to eliminate the impact of thermal deformations on the deformation of structural elements. Such expansion joints are usually made by cutting wet cement mortar, creating a grid of squares of 2.0 m to 3.0 m. Assuming a distance between the expansion joints of 3.0 m and temperature differences $\Delta T = 70$ °C, the change in the length of the substrate element (under the roof covering) under thermal load is max. approx. 2.1 mm, which is compensated for by the width of the expansion joint. With greater elongation of the roofing sheet covering (due to a different coefficient of thermal expansion) and the resulting difference in elongation, damage to the roofing sheet may occur due to stresses exceeding tensile strength or insufficient adhesion of the roofing covering to the substrate.

When analysing the durability of roofing sheet in roofing coverings, the cyclical nature of thermal loads should also be taken into account. This fact should be considered when assessing the effect of temperatures on the technical condition of bitumen roofing sheets and their possible damage. The research results regarding this phenomenon that have been published so far in the technical literature confirm that, as a result of repetitive cycles of opening and closing, the gap formed between the slabs of the concrete substrate horizontal plate movements, from 0 to 2 mm, on the surface of which waterproofing layers are laid, when simulated at variable temperatures: −15 °C and +70 °C, damage to the roofing layer can occur, even if it is made of roofing sheet with high values of maximum tensile force and/or elongation at maximum force [17]. For example, after 100 cycles of opening and closing the gap between the substrate plates at −15 °C and another 100 cycles as above at +70 °C, occurring in both cases at a testing speed of 16 mm/h:

- Bitumen sheet with reinforcement of polyester non-woven fabric and SBS-modified coating mass, at average maximum tensile force: 1034 N/50 mm and relative elongation at maximum tensile force on average: 44.9%, was not damaged above the test joint;

whereas:

- Bitumen sheet with reinforcement of glass fabric and SBS-modified coating mass, of average maximum tensile force 1498 N/50 mm and relative elongation at maximum force 5.0%, cracked locally over the test joint in the entire cross-section, while in the case of bitumen sheet with the same kind of reinforcement, but with oxidized bitumen coating mass, of maximum tensile force on average: 1750 N/50 mm and relative elongation at maximum force on average: 7.5%, the crack occurred only in the top layer of the coating mass.

These results were obtained in the test carried out in the apparatus shown in Figure 3 [17].

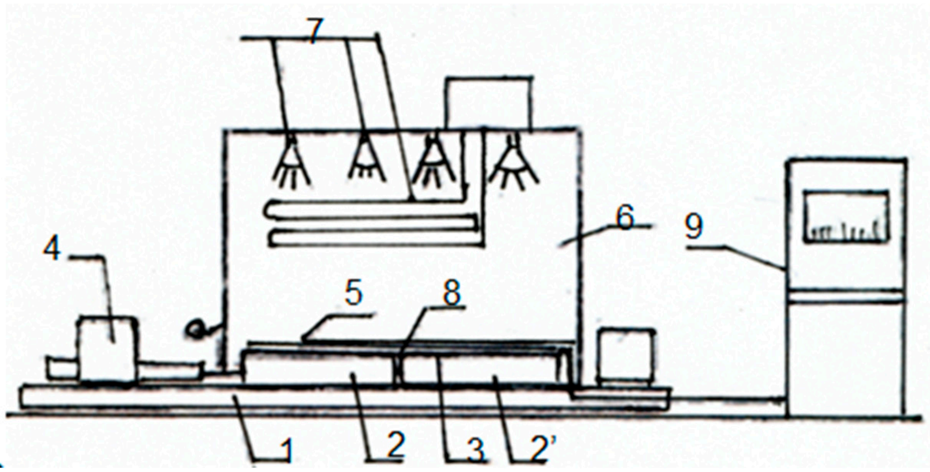
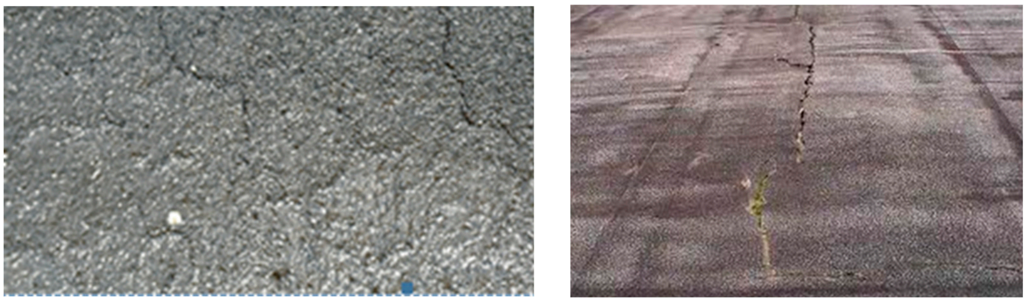


Figure 3. For testing resistance to fatigue—block diagram of the device: 1—base, 2—concrete slab of the substrate with the possibility of horizontal movement, 2′—immobilised concrete slab, 3—tested waterproofing layer, 4—electric actuator, 5—thermocouples, 6—temperature chamber, 7—heating lamps/variable cooling device, 7—temperature recorder, 8—gap between two concrete substrates, and 9—temperature recorder.

However, the cited publication lacks data on the stresses that occur when the roof covering is damaged. Only the velocity of movement and information on the absence or detection of cracks after completed test cycles are known. It is undeniable that the mentioned observations are very important from the operational point of view and should be treated as an important signal indicating the need for further studies on the durability of roofing sheet coverings in terms of mechanical damage caused by cyclical thermal deformations of the substrate at variable negative and positive temperatures. The presented results indicate that the effects of these actions are significantly affected by both the type of roofing sheet coating mass modifications and the tensile mechanical properties of roofing sheet, with particular emphasis on elongation at maximum tensile force. Naturally, it should be assumed that the damage process progresses successively over time, starting with cracks in the coating mass. The cracking in roofing sheet in the entire section does not occur immediately. However, bearing in mind that it is the continuity of coating masses covering roofing sheet strips that guarantees tightness to water and moisture, it can be concluded that such damage indicates the prior loss of serviceability of the assessed roof covering. Figure 4 shows examples of such failures.



(a) (b)

Figure 4. Surface damage to the roofing sheet: (**a**) hairline cracks in the coating mass, and (**b**) cracks in the roofing sheet, with visible traces of biological corrosion in the place of damage.

3. Conclusions

Although roofing sheet coverings have been in use since the 18th century and have undergone a major metamorphosis since then, to this day, not all mechanisms affecting their durability are known. An important, though not fully-explored scientific problem is the mechanism behind the way in which variable positive and negative temperatures affect roofing coverings during their operation and their impact on the resistance of roofing sheets to mechanical damage. Furthermore, the effect of interaction within the roof covering of two contact materials with different coefficients of thermal expansion, i.e., the concrete substrate and the roofing sheet, is still unexplained, which may also be a potential cause of damage to roofing coverings during their operation.

The analysed examples permit the conclusion that there is no direct correlation between the unit value of the linear expansion coefficient of the substrate, the durability of the roof coating resulting from repeated actions simulated in the quoted tests of resistance and the fatigue caused by the work of substrate panels at variable positive and negative temperatures. It is also recommended that this problem should be analysed periodically. Paper [48] provides alternative methods of roof covering, the use of which, however, did not ensure the durability and tightness of the roofing at excessive wind gusts. Numerical analyses of the effect of moisture on roof coverings were cited in [49,50], where it was clearly stated that the thermal conductivity coefficients of materials depend on moisture content of the material used.

The durability of roofing sheet coverings has a considerable impact on the durability of buildings, since most processes that destroy the substance of buildings occur in the presence of water and moisture. For this reason, it is vital to ensure the longest possible period of failure-free operation of roofing materials. Monitoring of roof coverings and proper diagnostics of their damage is a key issue from the point of view of all users of buildings [34]. However, to meet this requirement, it is necessary to know the processes that significantly affect the proper selection of roofing solutions for specific service loads. Although the possible destruction of the roof covering at the time of its creation is not a construction disaster, its destructive character lasting for a long time may consequently lead to a failure or a construction disaster [35].

Summing up, as part of their further work, the authors foresee the need to examine the mechanism of stress formation in roofing sheet layers, arising from variable positive and negative thermal loads acting on roof coverings, with the simultaneous need for cooperation in these conditions between two materials with different coefficients of thermal expansion. The following research tools are planned to be used to clarify this problem:

- Tests on the level of stresses that occur in the roofing-substrate system due to thermal loads;
- Numerical simulation of the system as above with different types of roofing sheets and real physico-chemical parameters of materials (experimentally verified).

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