Politechnika Lubelska
Wydział Budownictwa i Architektury

BUDOWNICTWO I ARCHITEKTURA

Vol. 21(3) 2022

Politechnika Lubelska
Lublin, 2022

Politechnika Lubelska
Wydział Budownictwa i Architektury

BUDOWNICTWO
I ARCHITEKTURA

Vol. 21(3) 2022

Politechnika Lubelska
Lublin, 2022

Adres redakcji/Address:
Politechnika Lubelska, Wydział Budownictwa i Architektury
ul. Nadbystrzycka 40, 20-618 Lublin, e-mail: wb.bia@pollub.pl

Strona czasopisma/Journal website:
https://ph.pollub.pl/index.php/bia/

Indeksacja/Indexed in:
Arianta, BASE, BazTech, CEEOL, Dimensions, DOAJ, EBSCO, ERIH Plus, Google Scholar, Index Copernicus, Infona, PBN/POL-Index, Publons, Sherpa Romeo, TIB, WorldWideScience

Publikacja wydana za zgodą Rektora Politechniki Lubelskiej.
Published with the consent of the Rector of Lublin University of Technology.

Finansowana w ramach środków Ministra Nauki i Szkolnictwa Wyższego.
Financing by the Polish Ministry of Science and Higher Education.

ISSN 1899-0665

Realizacja/Published by: Biblioteka Politechniki Lubelskiej
Ośrodek ds. Wydawnictw i Biblioteki Cyfrowej
ul. Nadbystrzycka 36A, 20-618 Lublin, email: wydawca@pollub.pl

SPIS TREŚCI

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Budownictwo i Architektura 21(3) 2022, 5-18
DOI: 10.35784/bud-arch.2927

Received: 22.04.2022; Revised: 16.06.2022;
Accepted: 27.06.2022; Available online: 31.10.2022

Orginal Article

Application of sawdust concrete in construction

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Abstract: Sawdust concrete is a type of lightweight concrete in which some of the mineral aggregate is replaced by sawdust – a by-product of wood processing. It is not a new material, but its potential is not utilised to its full degree. Taking into account the most important advantages of sawdust concrete – lower density and greater thermal and acoustic insulation than ordinary concrete – it is worth to consider the possibilities of its usage in construction wider than currently. In order to present the properties of sawdust concrete, the review of contemporary technical literature has been performed.

For the production of sawdust concretes mineralized sawdust from various types of trees, ordinary cements, mineral aggregates and water, are used. The usage of additives and admixtures is also allowed. The properties of the finished sawdust concrete are mainly influenced by the proportion of its components, especially the amount of fine aggregates replaced by sawdust. The construction products made of sawdust concrete are characterized by a low coefficient of thermal conductivity λ and soundproofing properties. In bending tests, a simply supported sawdust concrete beam behaves similar to a regular concrete beam, cracks first appear in the tension zone. Tensile strength, compressive strength and Young's modulus of sawdust concrete products depend on the proportion of components and the method of sawdust preparation before applying in the sawdust concrete-mix. Compared to ordinary concrete, the obtained values for sawdust concrete are lower, but partially fall within the ranges for the lower classes of ordinary concrete.

There are several possible applications of sawdust concrete in construction. One of the perspectives is to use it to build walls in buildings that require soundproofing between rooms, or to replace wood with it when renovating old buildings. However, further tests of sawdust concrete are needed in terms of the most favourable composition for its mechanical properties, and to define the standards according to which sawdust concrete elements should be produced.

Keywords: concrete, sawdust, sawdust concrete, construction, green building

1. Introduction

1.1. Principles of sawdust concrete

Intensive construction activity involves the use of large amounts of materials, especially those of natural origin, such as aggregates, and the production of tons of waste. The construction industry is responsible for about 25% of global greenhouse gas emissions [1]. Therefore, one of the challenges facing the construction industry should be to reduce its harmful impact on the environment and to use the available materials more efficiently.

A material which can respond to such needs is sawdust concrete – a type of lightweight concrete wherein sawdust replaces part of the traditional aggregates [2], [3]. It is not a new material, however, it is not as popular as it could be due to its ecological potential.

The sawdust used for production of the sawdust concrete is a by-product of carpentry processing. Their use for production of the concrete allows to reduce the consumption of natural aggregate and reduces CO_2 emissions. The big advantage of sawdust is its low price and easy availability, thanks to which the use of this material for production of the concrete does not generate additional logistical problems or costs. This is an advantage of sawdust over mineral aggregates – the latter with a constantly growing price and a limited area of extraction, which results in high transportation costs [1], [4].

This paper presents the characteristics of sawdust concrete and its components, as well as a description of its properties, in comparison to regular concrete grades.

1.2. Sawdust

More than 20 million m^3 of sawdust are produced annually in the world, most of which is incinerated. This leads to an increase in air pollution and greenhouse gas emissions [5]. Effective use of that raw material, e.g. for production of composite materials, is in line with ecological considerations. It would also contribute to savings in materials and costs of construction projects [3], [5]. The summary cost presentation of obtaining 1 m^3 of sawdust, gravel and sand is presented in Table 1 [6]. The presented table shows that the chips contribute to a multiple reduction in carbon dioxide emissions, and their transport uses about 7 times less energy – compared to sand and gravel.

Table 1. Summary of CO_2 emission and energy used for the transport of concrete components. *Source*: [6]

Material	Sawdust	Gravel	Sand
CO_2 emission [t/1 m^3 of the material]	0.0007	0.012	0.009
Energy used [GJ/1 m^3 of the material]	0.0195	0.148	0.134

The bulk density of sawdust, depending on its structure and the type of wood it comes from, ranges from about 160 to about 260 kg/m^3.

Fig. 1. Beech wood sawdust. *Source:* [7]

The available literature does not specify which types of wood are used to obtain sawdust with the best results as a material for the production of sawdust concrete. The available research shows use of chips from – for example – juniper, beech (Fig. 1), spruce, pine, fir and padauk trees [1], [3], [8]-[11]. Authors of mentioned papers used local species obtained from nearby sawmills and other wood processing centres.

Fig. 2. Fine sawdust. *Source:* [12]

Similarly to the types of wood from which sawdust is obtained, the recommended sizes of sawdust are not specified. Usually, the research uses sawdust with the largest size in the range 0.1 – 8 mm [3], [8]. It is also suggested to use a smaller maximum dimension of 5 mm [1], [10] or, on the contrary, up to 10 mm [11]. Another approach is to take the largest size of the sawdust as close as possible to that of the aggregate it is replacing. In the case of tests where fine sawdust (Fig. 2) replaces some of the fine sand, chips with a maximum dimension of 2 mm were used – to make the size of the wood particles as close as possible to the diameter of the sand grains [5].

Sawdust is an organic material, which means that special attention should be paid to protecting them against rotting and decaying. It was determined that the content of organic particles did not make the material susceptible to fungus [13]. However, it is also necessary to use certain substances to minimize the destruction of sawdust and the impact of other concrete components on them, through their mineralization [14]. Such preparation of sawdust reduces the strength drop of sawdust concrete [2].

There are various terms for small wooden particles, e.g. sawdust, shavings, wood dust, presented in literature. However, no standard name distinctions are given with regard to the size of the wood particles. For this reason, this article will not devote any space to linguistic discussion, and different names for the wooden filler will be used alternately.

1.3. Sawdust concrete

Sawdust concrete is a type of lightweight concrete in which sawdust replaces part of the traditional aggregate [2], [3]. An example of sawdust concrete block is shown in Fig. 3.

Portland cement plays the role of a binder [14]. It is possible to add additives and admixtures to sawdust concrete. As a result of the combination of wood and concrete, a material with a lower density and greater thermal and acoustic insulation than regular concrete is obtained [13], [15].

Fig. 3. Sawdust concrete block with 5% fine sawdust. *Source:* [16]

Due to different physical and chemical properties, direct connections between concrete and wooden elements are not used in construction. However, with proper preparation and combination of these materials, sawdust concrete is obtained, which is suitable for use in construction. Protected, e.g. by mineralization, the sawdust does not exhibit the negative properties of wood, e.g. they do not decompose, do not rot and do not have high water absorption. Mineralized sawdust does not hinder the cement setting process and the production of sawdust concrete itself does not differ significantly from the production of regular concrete. It is worth noting that the addition of sawdust does not affect the homogeneity of the concrete mix [3].

As the sawdust content increases, the mechanical properties of sawdust concrete deteriorate. This is because the strength of the material decreases as compared to regular concrete [2], [3]. Studies have shown that the durability and strength of sawdust depends on the texture, size and angularity of the wood particles [1]. Thus, it is only suitable for construction elements to a limited extent. However, it is worth noting that not all potential uses of sawdust in construction require high strength parameters.

When sawdust is mixed with cement and water, the organic material may begin to soak up with water, thus disturbing the water-cement ratio and reducing the amount of water available for the cement hydration process [9]. As the water absorption of sawdust increases, the material's freeze thaw durability decreases [1]. Unprepared, e.g. by mineralization, the shavings also slow down the hydration and hardening process of the mortar [4], [10]. Therefore, it is important to mineralize the sawdust before applying it to concrete. On the other hand, researchers noted the advantage of using non-mineralized sawdust. The water taken over by them during the mixing of the mortar later helps in the cement hydration process in places where it is not possible to add water during setting, for example in the middle of the poured layer [2], [4]. The tests performed for sawdust concrete samples with the use of 3-8 mm size sawdust have shown that the organic filler reduces capillary absorption inside the material [9].

2. Production of sawdust concrete

2.1. Ingredients

2.1.1. Organic material – sawdust preparation

Fig. 4. Fine sawdust before (left) and after (right) drenching it in a protective mixture made of cement and water. *Source:* [3]

Chips used for production of sawdust concrete need to be mineralized. Calcium chloride is used for this purpose – thanks to the supersaturation of natural wooden aggregate, it is protected against quick deterioration [13]. Chromated copper arsenate (CCA) is another substance used to protect sawdust [11]. Some sources suggest treating sawdust with broadly understood alkali [5]. Another approach proposed by some researchers is, in order to improve the adhesion between the cement and sawdust, placing the chips in a sodium silicate solution (100g/1l) 24 hours before mixing with other sawdust concrete components [9]. Also, protection of sawdust by prior coating it in a water-cement mixture (Fig. 4) in the cement-to-wood mass ratio of 2.5, results in increased strength and reduced shrinkage when setting concrete [3].

2.1.2. *Cement*

According to published research results, the CEM I and CEM II are the cements used for production of sawdust concrete [1]-[6]. However, it is not specified which cement is best for sawdust concrete, in terms of various factors, e.g. durability, strength. The use of these mixtures proves that known and common materials are selected for production, and that sawdust concrete does not require special cements.

2.1.3. *Aggregate*

Recipes for sawdust concrete vary depending on the research centre. They all share the use of fine sand, most often river sand [2] with a diameter of up to 5 mm [8]. It is an important component of sawdust concrete in terms of the proportion of components, because most often the amount of added sawdust is determined in relation to the amount of fine sand [2], [5], [11], [17]. Coarse aggregate [8] with an exemplary grain size of up to 9.5 mm [2] is also added to sawdust concrete. Granite aggregate can be used for the production of sawdust concrete [4], [5], however, in most research descriptions, the rock species from which the aggregate was obtained were not specified.

2.1.4. *Additives and admixtures*

Admixtures can be used to improve the properties of the mixture and the finished sawdust concrete, mainly to regulate the consistency and fluidity of the mixture, e.g. air entraining admixtures or stabilizers [10]. Some researchers have successfully added a superplasticizer to the mixture for sawdust concrete production [3], [8]. Successful trials of using additives and admixtures other than woodchips in sawdust concrete in laboratory tests prove that their use in sawdust concrete mixtures is right and safe.

Due to the fact that sawdust concrete has worse mechanical properties than regular concrete, the influence of other substances on the properties of sawdust concrete is also tested. It was verified that the addition of pozzolana in the amount of 10% increases the compressive and tensile strength of concrete. It is also important to note that the mentioned additive increases the durability of sawdust concrete [18].

2.2. Production of sawdust concrete

2.2.1. *Ingredients proportions*

The proportions of the ingredients are important to obtain the desired properties of the final material. The number of available studies on the determination of the quantity of aggregate that should be replaced with sawdust, favourable for the various properties of sawdust concrete, is small. Researchers do not agree on this point. The most common values in the studies are 5-30% [5], [11]. These are the proportions, according to recommendation, by volume [17]. However, the limit values have not been clearly defined – due to the insulating properties of sawdust on the one hand and the strength parameters of the resulting sawdust concrete on the other.

Usually, the water-cement ratio in sawdust concrete ranges from 0.4 to even 1.2 [17]. Examples of cement/sawdust/water ratios are: 1/0.46/0.7 and 1/0.22/0.7 [3], 1/0.27/0.75 [9], 1/0.16/0.61 [10]. Also mixtures with more sawdust were used for the tests – the cement to sawdust ratio was 0.67 [17] or even 0.81 [1]. Another proportion of the proportion of concrete solids, which is repeated in studies on sawdust concrete, is 1/2/4 (cement/sand/granite aggregate) [4], [5]. These discrepancies testify to the constant search for the best proportions of ingredients for the properties of sawdust concrete.

2.2.2. Manufacturing method

The production technology of sawdust concrete and preparation of samples made from this material is very similar to technology used for regular concrete. The first step for production of the sawdust concrete is the accurate weighing of all ingredients – initially in separate containers. Then the coarse and fine aggregate and cement are mixed together. Then sawdust is added and mixed again. Only then is water gradually added while stirring. The production scheme for sawdust concrete mix is shown in Fig. 5.

Another approach is to mix the sand with the sawdust first. Then add cement and mix again, then add coarse aggregate and mix again. Add water to all mixed dry ingredients in accordance with the adopted proportion [2]. It should be borne in mind that the water necessary for the recipe is the water needed by the concrete mix and the water that will be absorbed by the sawdust [19]. The latter amount has not been presented in the available literature so far. However, it is clear that the amount of water depends on the type of sawdust used.

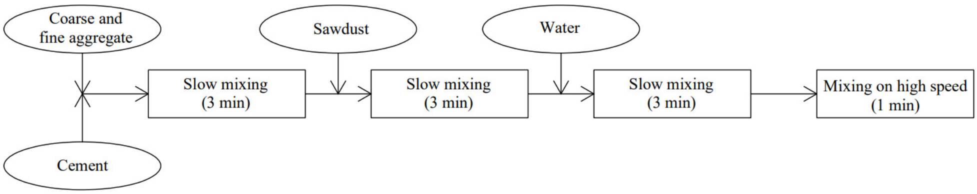

Fig. 5. Diagram of sawdust concrete mix formation. *Source:* [1]

For drying of cast sawdust concrete elements, conditions similar to those for regular concrete are assumed. However, it is not specified whether this affects the properties of the finished sawdust concrete or whether it was just considered appropriate to base on known conditions.

After casting, the sawdust concrete blocks can also rest in conditions of high relative humidity, reaching 90-97%, for the first 1 to 7 days. Later the humidity is lowered to 50%. The ambient temperature should be 20^{o}C [3], [9].

Due to the reliable comparison of test results with elements made of regular concrete, elements made of sawdust concrete are also tested on strength machines after 28 days [3], [10], [17].

3. Properties of construction elements made of sawdust concrete

3.1. Physical properties

Density is a feature that translates directly into the weight of the finished element. The density of sawdust concrete decreases with an increase in the percentage of fine aggregate replaced by organic material [2], [3]. The exact value depends on the ratio of components and is in the range of 760-1880 kg/m^3 [5], [9], [10]. This allows the material to be classified as lightweight concrete, because its density does not exceed 2000 kg/m^3.

Air content in sawdust concrete depends on the sawdust percentage. This issue has not been well studied yet, however according to [20] the more sawdust used, the higher the air content and its value is in the range of 5.5%-14%.

One of the technically significant benefits of sawdust concrete is its low thermal conductivity coefficient λ (W/(mK)). Its value, depending on the sawdust content, ranges from 0.2 to 1.0 [3], [10], [13]. For comparison, the value of λ for regular concrete is up to 1.7, so the use of sawdust concrete can increase the thermal insulation of the wall.

Sawdust concrete also has sound-absorbing properties. Elements made of this material can be used as a good acoustic insulation due to the ability of sawdust concrete to extinguish sound waves [1], [9], [13].

Sawdust also reduces the electrical resistance of sawdust concrete – it is lower compared to regular concrete [18].

It is indicated that fire may cause a reduction in the volume of the concrete sample or a change of its colour to a darker shade [11], [21]. Since the fire resistance of sawdust concrete has not been well studied so far, it should not be recommended to apply sawdust concrete for fire-rated walls.

3.2. Water absorption

Water absorption is defined as the ratio of the difference between the mass of a material fully saturated with water and a material in a dry state to the mass of a material in a dry state, expressed as a percentage. The aim is to minimize water absorption, because the presence of water in the pores of the concrete negatively affects its properties. The measured water absorption of sawdust concrete was 29.7% [1], some the results were also below 20% [2]. The values, however, vary depending on how the sawdust was treated prior to mixing with the cement. Nonetheless, there are no studies that could clearly determine the relationship between the method of sawdust preparation and the absorbability of sawdust concrete.

Still, it is importantfor the obtained water absorption values to be below the limit value of 30%, above which the material would suffer deformations as a result of freezing and thawing water [22]. This allows us to argue that this parameter does not prevent the use of sawdust concrete for the construction of internal and external walls of buildings.

3.3. Mechanical properties

The most important mechanical properties in terms of use in construction are: compressive strength, flexural strength and Young's modulus. Determination of the ranges within which the expected and obtainable mechanical properties for sawdust concrete are important for the possibility of subsequent calculation of elements made of this material.

The compressive strength of sawdust concrete is measured, just like regular concrete, on cubes with dimensions of 0.1x0.1x0.1 m, after 28 days. The results obtained from the research are in a wide range, from about 5 to even 46.4 MPa [3], [9], [17], [23]. The discrepancies in the results occurred due to different proportions of sawdust concrete components, the mineral aggregate and class of the cement used and the conditions in which the samples dried. It was verified that too high humidity in a room with sawdust concrete elements resulted in a decrease in compressive strength with time [9].

The relationship between flexural (f_b) and compressive (f'_c) strength in sawdust concrete depends on the amount of aggregate replaced with sawdust and the class of concrete used. The ratio between those two strengths f_b/f'_c varies between 0.07 and 0.17 based on the research available [11], [17], [20].

In bending tests of simply supported sawdust concrete beams, they behave similarly to regular concrete beams – cracks first appear in the tension zone [1]. The tensile strength of sawdust concrete, determined in such tests, is in the range of 1.9 – 6.4 MPa [2], [10], [17].

The Young's modulus E for sawdust concrete determined in the research ranges from about 7 to 20 GPa [2], [17]. The obtained values depended on the water-cement ratios of the mixture and the amount of fine sand replaced with sawdust. A greater reduction of Young's modulus could also be influenced by an inappropriate proportion of sawdust concrete components – in the same tests for a mixture without sawdust, depending on the water-cement ratio (0.37-0.57), Young's modulus in the range of 15.23-22 was obtained [2].

It is possible to compare the obtained values to those given for concrete according to PN-EN-1992. Depending on the class of concrete, the characteristic cube compressive strength ranges from 15 to 60 MPa, therefore some values obtained for sawdust concrete fall within this range. The obtained values of Young's modulus for sawdust concrete are much lower than the European standards for concrete, for which, depending on the class, the modulus of elasticity ranges from 27 to 37 GPa. However, it should be noted that for sand aggregates, which were partially used in the tested sawdust concrete, the Young's modulus of concrete decreases by 30%, which gives the range of 18.9 – 25.9 GPa, which already includes some of the results obtained for sawdust concrete.

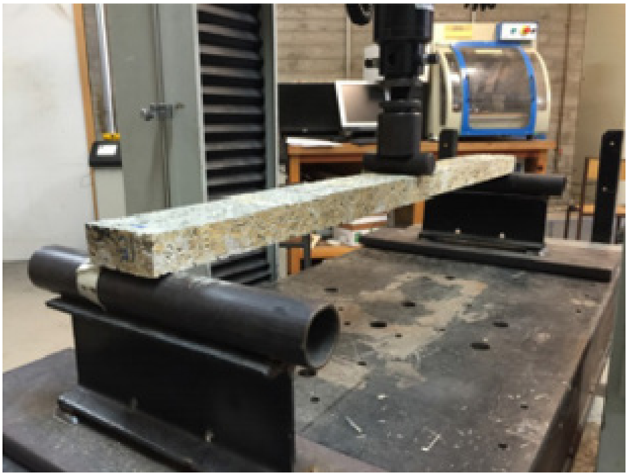

Fig. 6. Bending test of a simply supported beam made of sawdust concrete. *Source:* [1]

In order to better illustrate the tensile strength of sawdust concrete, in Table 2. the tensile strength σ (MPa) maximum values of the P force (kN) that can be loaded on a beam made of various materials in the bending test of a simply supported beam are listed (Fig. 6.). The calculations were made for a beam of 0.04x0.1m section and length l=1.0m, for which the bending index $W = 6.67 \cdot 10^{-9}$ (m^3). The maximum value of the force P (kN) was calculated from the Eqs 1-3:

$$\sigma = \frac{M}{W} \quad (1)$$

$$M=\frac{Pl}{4} \tag{2}$$

$$P=\frac{4\sigma W}{l} \tag{3}$$

The summary clearly shows that sawdust concrete has lower tensile strength than metals, glass and even wood. However, the value of the maximum loading force P (kN) is greater than for concrete of the C20/25 class. There has been too little research investigating the potential improvement of the mechanical properties of sawdust concrete compared to concrete to draw far-reaching conclusions. It shows, however, that sawdust concrete does not have any strength properties inferior to the currently used building materials.

Table 2. Summary of the tensile strength and the maximum value of the force loading the beam. *Source: own study*

Material	Steel	Aluminum alloy	Glass	Concrete C20/25	Wood	Sawdust concrete (averaged)
Tensile strength (MPa)	540	215	30	2.6	87	4.15
P_{max} (kN)	144	57.33	8	0.69	23.20	1.11

Replacing some of the aggregate with sawdust does not change the failure pattern of concrete cylinders under compression [20]. The mechanism of sawdust concrete failure during bending is similar to regular concrete test. The effect of failure first occurs in the tension zone [1].

4. Application of sawdust concrete

4.1. Use in construction

Sawdust concrete is suitable for the production of prefabricated elements. It is not recommended to use it in structural elements [16]. Internal walls and ceiling panels can be made of sawdust concrete. Water absorption below 30% allows it to be used also for external walls, which are even exposed to negative temperatures [1].

Due to the lower value of the thermal conductivity coefficient than in regular concrete, it is possible to produce elements of thermal insulation layers [5], [9]. Due to the greater stiffness as well as acoustic and fire resistance compared to wooden elements, sawdust concrete can be used as a substitute for wood in the renovation of older buildings [7]. Thanks to its sound-absorbing properties, sawdust concrete can be used in elements that would simultaneously have a barrier and soundproofing function, e.g. as partition walls in cinemas, theatres or music schools.

It is important to note that sawdust concrete can be processed with tools whose primary application is wood processing [13]. This allows blocks to be processed quickly with commonly used and readily available equipment. This is especially important at a construction site when it is necessary to cut the block, e.g. in case of dimensional inconsistencies, unevenness or in order to obtain an equalizing block.

4.2. Other perspectives

Attempts were made to create composites of wood and sawdust concrete. Slabs made of such a composite, glued with epoxy or polyurethane, met the requirements for stiffness and flexural strength [7].

Elements made of sawdust concrete can be produced by 3D printing. The workability and lightness of the mixture are the positive features of sawdust concrete used in this technique, thanks to which sawdust concrete performs better than regular mineral mixtures. Elements made of sawdust concrete were made more precisely and with greater ease than those made of regular concrete mix [10].

5. Conclusions

Sawdust concrete is one of the "green building" materials, and its use allows for the reduction of construction costs. Taking into account the widespread interest in reducing the amount of waste from the construction industry and concern for the development of environmentally friendly technologies, the use of sawdust for production of the concrete can be considered a rational solution. In addition, the cost of producing sawdust is lower than mineral aggregate, shavings are also more easily available. This reduces the emissions and costs of production and transport of the material for the production of concrete.

Mechanical properties of sawdust concrete do not differ significantly from those of concrete of lower strength classes. The conclusions drawn from the research prove that obtaining the highest possible values of strength parameters will be possible when the most favourable proportion of components, the type of aggregate and the method of sawdust preparation are determined in terms of the impact on the mechanical properties of sawdust concrete.

The advantage of sawdust concrete is its acoustic and thermal insulation properties higher than for regular concrete. It creates many perspectives for using that material in insulation layers for various objects. For example: in partition walls of residential buildings, theatres, cinemas and as an insulating base in floors.

It was also found that sawdust concrete is a material liked by animals. Currently, birdhouses are made of this material. One of the prospects for the future is the use of sawdust concrete in livestock facilities.

In the world of construction, where various standards are omnipresent, guidelines for its production and use are necessary for the effective introduction of a new material on a large scale. For the further development and application of sawdust concrete technology, it is necessary to determine the recommended ratios of components and, in particular, the percentage of sawdust. It is also necessary to define the conditions to be met by sawdust so that the produced sawdust concrete is safe for use in the structure and durable. There is also a clear lack of standards defining the target ranges in which the values of various quantities characterizing sawdust concrete, such as: density, compressive strength, water absorption, should fall.

Due to the fact that sawdust is an organic material, it is necessary to take a closer look at the durability of sawdust concrete over a longer period of time. It is also recommended to further investigate potential changes in strength characteristics with time.

Funding

The research has been carried out within the framework of the Operational Program Knowledge Education Development, Ministry of Science and Higher Education, Poland. “Masters of didactics” under Measure 4.3 Transnational cooperation project no. MNiSW/2020/114/DIR/WMT/W01, ZSI:11MO/0001/20

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Budownictwo i Architektura 21(3) 2022, 19-34
DOI: 10.35784/bud-arch.2886

Received: 20.03.2022; Revised: 19.09.2022;
Accepted: 27.09.2022; Available online: 31.10.2022

Orginal Article

Wind aspects in a built-up environment

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Abstract: The dynamic development of built-up areas observed in the last few decades resulted in strong environmental transformations, especially in terms of climate phenomena. One of the factors which significantly affects the climate and bioclimate of urban areas is wind. Wind can cause discomfort to pedestrians or heat loss in buildings, if the wind speed around buildings is too high. The paper presents two examples of research conducted by the author, related to the issues of wind flow in built-up areas, based on the numerical simulations. The numerical simulations become an increasingly frequently used tool to determine the wind climate. Simulation results provide designers with important information on the influence of the buildings and their layout on the local changes in airflow. They allow testing of alternative solutions and effectiveness of various remedial measures.

Keywords: wind, urban structures, comfort, heat loss

1. Introduction

The dynamic development of built-up areas observed in the last few decades resulted in strong environmental transformations, especially in terms of climate phenomena. In addition to natural factors shaping the climate, such as latitude, topography, or the presence of water reservoirs, the anthropogenic factors directly related to human activity have gained in importance. Changes in atmospheric environment and modification of the climate of cities are mostly influenced by:

- intensive emission of pollutants into the atmosphere, related to industrial production, transport or buildings;
- emission of waste heat or heat lost in technological processes and energy devices as well as heat used for heating buildings;
- disruption of natural thermal, humidity and radiation balance due to the large share of artificial substrate (roofs and walls of buildings, street surfaces, etc.) and small amount of greenery;

- decrease in global air exchange with compact buildings and thus increased ground roughness.

Excessive heat, changes in air movement, and changes in the physical and chemical composition of the air have become characteristic features of modern cities.

Such intensive environmental transformations cause the need for decisive measures to improve the quality of life in cities. Implementation of the principles of sustainable development is one of the ways to ensure harmonious growth of urban areas. An important role in this regard is played by the construction industry, recognized as one of the six pioneer markets in the EU, i.e., markets particularly susceptible to innovation and with a high potential for development [1]. Implementation of new technologies and solutions in the construction industry has been considered particularly important due to its impact on the three main pillars of sustainable development – environment, economy, and society. The environmental aspects of sustainable development generally refer to the protection of natural resources, the consumption of which is assessed in relation to the technical life cycle of materials, construction products, as well as the entire building. However, in the context of the development of built-up areas, it becomes more important to extend these issues to additional physical elements affecting the quality of life, i.e., sunlight, ventilation and noise exposure. For example, in the case of dense urban development, the interaction of wind and sun influences the energy efficiency of a particular development layout.

Proper ventilation of built-up areas affecting the improvement of aero-sanitary and micro-climatic conditions also becomes extremely important. At the same time, it is worth emphasizing the influence of development on the local wind conditions, which may sometimes lead to sudden increases in velocity and the creation of discomfort conditions for pedestrians. In this context, it is important to consider wind aspects in both land use planning and development design.

2. Wind flow in urban areas

As a result of the city's considerable surface roughness, the wind speed is significantly reduced. Detailed studies of Cracow climate have shown that the reduction of wind speed in the city center is on average 30%, decreasing in the outer zone housing development to 15-20% [2].

Considering the air flow on the scale of housing estate or compact structures of buildings, it should be noted that it is an extremely complex phenomenon. Direction and velocity of air streams are affected by the buildings, their size, layout, as well as the characteristics of the ground and turbulence. Consequently, the changes in wind conditions observed in the urban environment may have a positive or negative character. Unfavourable aspects may include an increase in wind speed near buildings, which can cause discomfort to pedestrians. At the same time, too low wind speeds cause insufficient ventilation of built-up areas and local accumulation of pollutants or snow.

Particularly unfavourable conditions appear in the case of tall buildings [3]. They tend to pull the flow down the walls and create strong turbulence near the ground surface [4]. In addition, the phenomenon of buildings interacting with each other can be observed, revealing disturbances in the pressure and velocity distribution in their vicinity [5, 6]. This results in adverse secondary flows that interfere with pedestrian comfort [7, 8].

Air movement in an urban area is a very complex phenomenon. The largest flow disturbances occur in the ground zone, where variable wind speed field and secondary flows are observed, forced by existing building masses. Changes in the horizontal profile are observed at a distance equal to ten to fifteen times the height of building, while in the vertical profile they reach up to three times the height of building [9]. The most important parameters shaping the airflow in built-up areas include: building length, width and height (L, W, H), direction of the inflowing airflow, z_o and $z_{o,loc}$ roughness parameters and thermal parameters. Despite many factors influencing the wind flow in the vicinity of a building, in each case it is possible to distinguish some characteristic flow zones with different degrees of influence.

As the wind flow approaches the building the air stream is separated and flows around the building (Fig. 1). The air flowing down the upwind wall creates a strong vortex at the ground level. Along the edges of windward wall, the air stream is broken off. The air flowing towards the building base forms vertical vortices, which after reaching the edge of a wall, along which there is a high negative pressure, experience acceleration creating strong side streams [4].

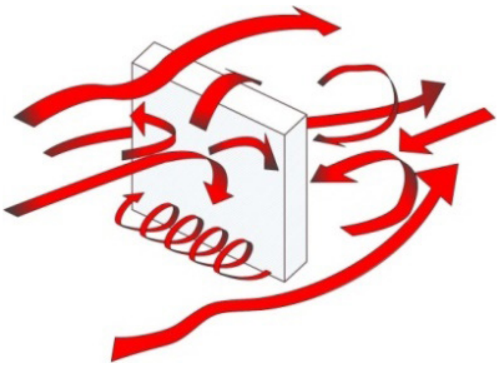

Fig. 1. Wind flow pattern on the windward side of the building. Adapted from [4]

Overcoming the obstacle involves the loss of part of the momentum, thus a zone of reduced flow is created behind the building. Part of the air flowing over the building returns, creating a recirculation zone, and part flows further, creating a far wake zone. Just behind the building, along the vertical edges of leeward wall, a system of vertical vortices forms, a so-called shear layer (Fig. 2.) [4].

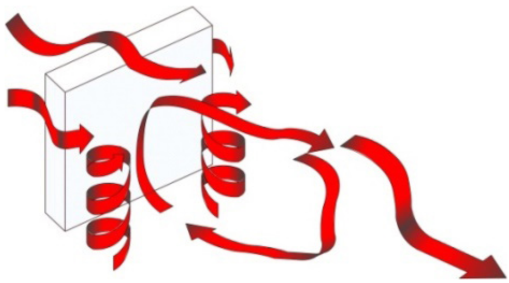

Fig. 2. Wind flow pattern on the leeward side of the building. Adapted from [4]

The Venturi effect occurs when two rows of buildings are located at an angle of less than 90° (Fig. 3). The length of buildings should not be less than 50 m and their average height not less than 15 m. The condition for the effect to occur is also the width of a gap between the buildings (1/2H < gap width < 4H) [10].

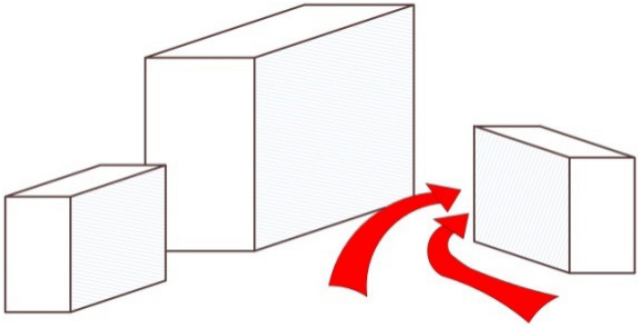

Fig. 3. The Venturi effect. Adapted from [4]

This arrangement of buildings affects the smooth change of flow cross-section which, depending on the wind direction, can cause an increase or decrease in velocity, without the formation of vortices. The increase of wind speed in the constriction is proportional to the height of buildings. For buildings 25 m high, the acceleration factor (defined as the ratio of velocity in the considered building system to the velocity at the same height, measured in the open area) is 1.3, and for buildings 45 m high the factor reaches the value of 1.6 [11].

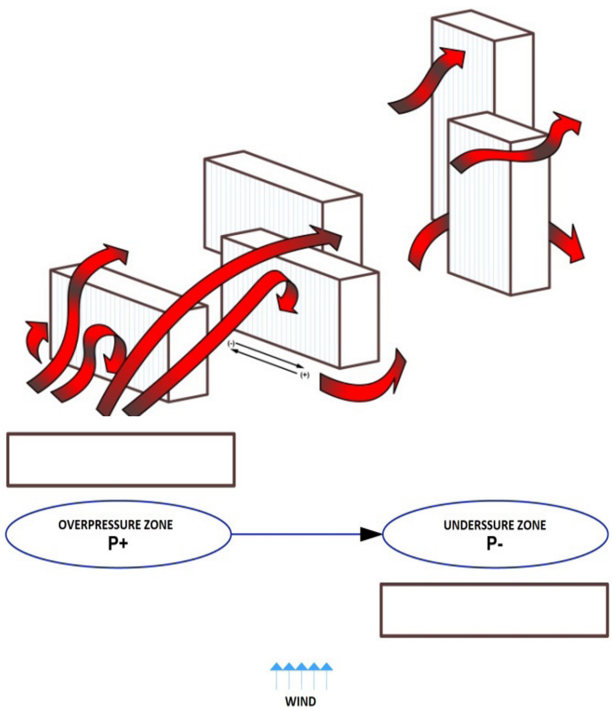

Fig. 4. Schematic representation of wind flow for two parallel buildings shifted towards each other. Adapted from [12]

Another effect, often observed in housing development, is the combination of overpressure and under pressure zones (Fig. 4). This effect occurs in the case of buildings arranged in parallel and additionally shifted in relation to each other. The pressure differences in the building walls result in an acceleration of the air flow from the overpressure zone towards the under-pressure zone. Research conducted by Beraneka in a wind tunnel and cited by Blocken in [12] indicates that pressure differences may be the cause of formation of extensive zones characterized by arduous wind conditions. The acceleration factor in these cases exceeds 2.0. The wind direction also deviates and remains parallel to the longer wall of buildings even at a considerable distance from the building.

The downwash vortex effect (Fig. 5) occurs when two buildings with distinctly different heights and a short distance apart (comparable to the height of the lower building) are adjacent. When the wind is perpendicular to the axis of buildings, there is a vortex of airflow in the zone between buildings, and near the corners of tall building, the air velocity increases significantly. Between the buildings, the acceleration factor can reach a value of 1.5-1.8 [13]. Side streams of a tall building show up to 96% increase in flow velocity [10].

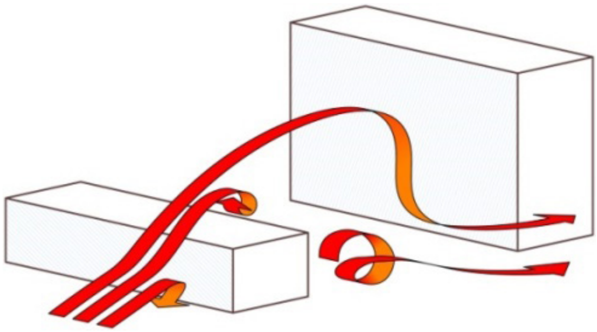

Fig. 5. The downwash vortex effect. Adapted from [4]

The characteristic flow zones around a single building presented above and the basic aerodynamic effects caused by the wind on buildings are disturbed for more complex building structures. Interaction of buildings with each other causes overlapping of individual zones. The result is the appearance of secondary flows, characterized by variable direction and velocity. In some cases, the wind direction changes to the opposite direction, which may cause unexpected feelings of discomfort.

3. Wind conditions at pedestrian level in complex urban structures

Wind flow in urban environment is characterized by sudden changes in directions and speed. In complex urban structures they are sometimes difficult to predict. There is a need for detailed analysis of wind conditions in the early stage of urban design. Numerical methods modelling wind flow around buildings become the useful tools for these purposes [14], [15], [16], [17]. A well-designed urban space should provide adequate ventilation and on the other hand protect pedestrians against too strong air flow.

The example of wind flow analysis from the pedestrian's comfort point of view has been presented below. In the analysed case the numerical simulation allowed to determine the areas of discomfort, where an excessive increase in wind speed was observed. To improve wind comfort in the vicinity of the buildings few kinds of shelter have been proposed.

The analysed building complex is located in the suburb of Warsaw. The buildings form two distinct interiors (Fig. 6). The layout of the buildings causes unpleasant air flows, especially in winter. On the west and south sides, the surrounding area is flat with single low obstacles. Adjacent buildings of similar height are located 150 m and 50 m away from the north and east respectively.

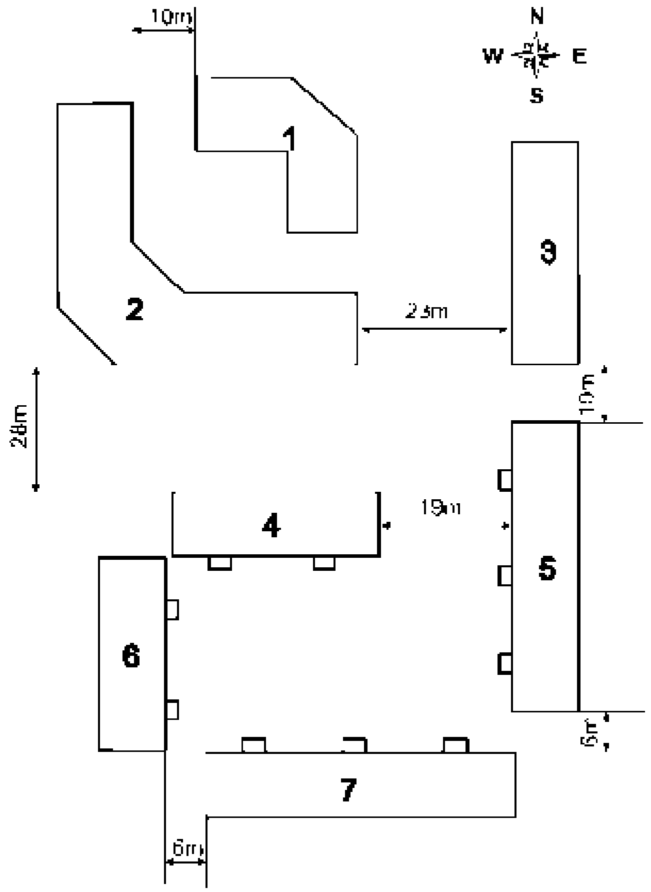

Fig. 6. The arrangement of buildings [18]

The analysis has been done for 8 wind directions and average wind speed for Warsaw, obtained over a 10 year period. Because pedestrians' comfort was the focus of the numerical simulations, wind speeds were analysed at a height of 1.8 m (pedestrian's height). The results were presented in the form of acceleration factor (V/V_o).

Wind flow analyses confirmed the presence of discomfort zones. For example, in the case of the west wind direction dominating in Warsaw the highest value of V/V_o reaches 1.8 were observed in the large canal formed between two interiors (Fig. 7). On the other hand, upstream buildings block the approaching wind and create a shelter zone inside the complex. Detailed information about wind flow pattern in the case of other wind direction can be found in [18].

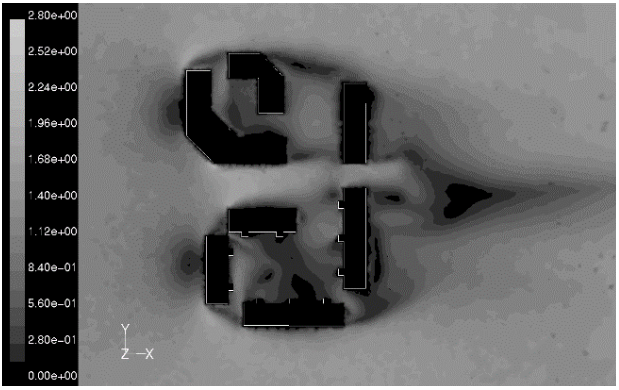

Fig. 7. Wind speed ratio for west wind direction [18]

To weaken the air flow, three types of windbreaks have been proposed: earth berm, acoustic screen, and shelterbelts. Location of windbreaks have been presented at the Figure 8a and 8b.

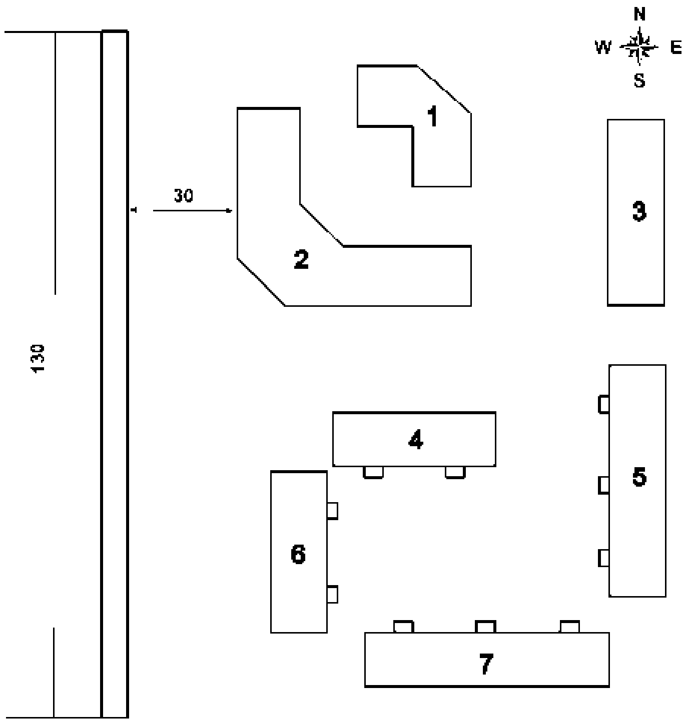

Fig. 8a. Location of the windbreaks and trees [18]

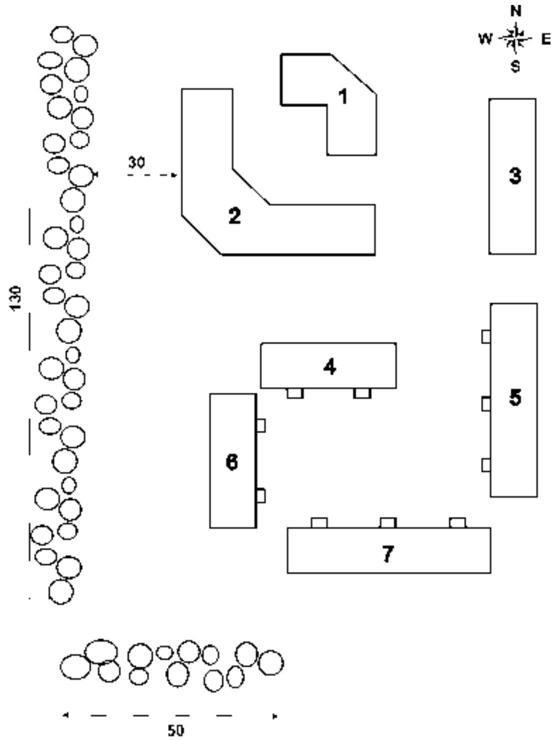

Fig. 8b. Location of the shelterbelts 2 [18]

Two kinds of shelterbelts have been considered. In the first case (shelterbelt 1) a row of trees was located as on the Fig. 8a. In the case of (shelterbelt 2) an additional row of trees has been introduced as a protection from the southwest winds (Fig. 8b).

Shelterbelts modelled in the simulation consisted of trees and shrubs. It allowed to reach a higher effectiveness. The dimensions of the shelterbelt were: 130 m x 7 m x 10 m (width, height, length). Two shapes of the crown have been included: cone – shaped crown representing a conifer and ball – shaped crown stands for a deciduous tree.

The earth berm was the next analysed case of windbreak. Its dimensions were: 130 m x 4 m x 10 m (width, height, length). To allow for additional plantings, the top of the earth berm was assumed to be flat.

As the building complex is adjacent to the street with traffic density of about 1000 vehicles per hour, an acoustic screen has been proposed to protect the residents from noise and wind. The acoustic screen was located in the western side of the building complex. Its dimensions were: 130 m x 4 m x 0.25 m (width, height, length). In that case the effectiveness of noise barrier in reducing sound levels is about 15 dB.

In the case of wind inflow from the west direction, all kinds of windscreens reduced air flow in a canal between two interiors. (Fig. 9). Near the upstream corners of the buildings maximum value of V/V_o changes from 1.7 to 1.46.

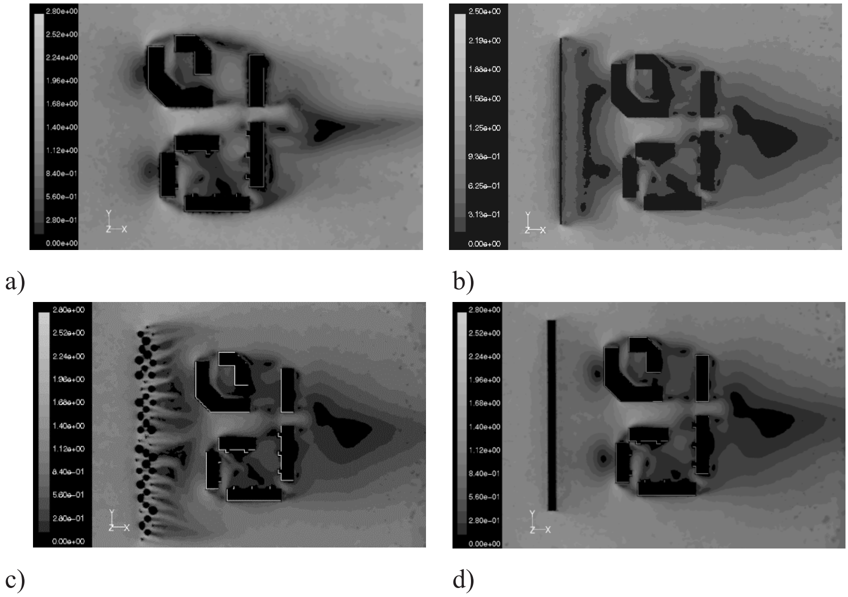

Fig. 9. Wind speed distribution in analysed complex: a) without shelter, b) with acoustic screen, c) row of trees and d) earth berm [18]

Distribution of V/V_o in the passage between buildings 2 and 4 for all analysed cases has been shown on Fig. 10. The use of wind screens, regardless of their type, brought the desired effect. The maximum reduction in V/V_o, about 0.7 have been achieved for shelterbelts both with one and two rows of trees.

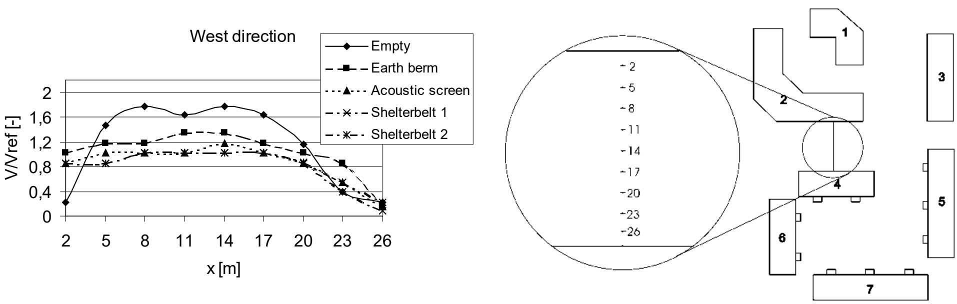

Fig. 10. Distribution of V/V_o ratio in the corridor between buildings 2 and 4 for different windbreaks and west wind direction [18]

In the case of southwest wind direction, the pedestrians' comfort is seriously affected, especially in the passage between buildings 6 and 7. Application of windbreak partially reduced the wind speed in this area. Figure 11 shows distribution of V/V_o ratio in the analysed narrow passage.

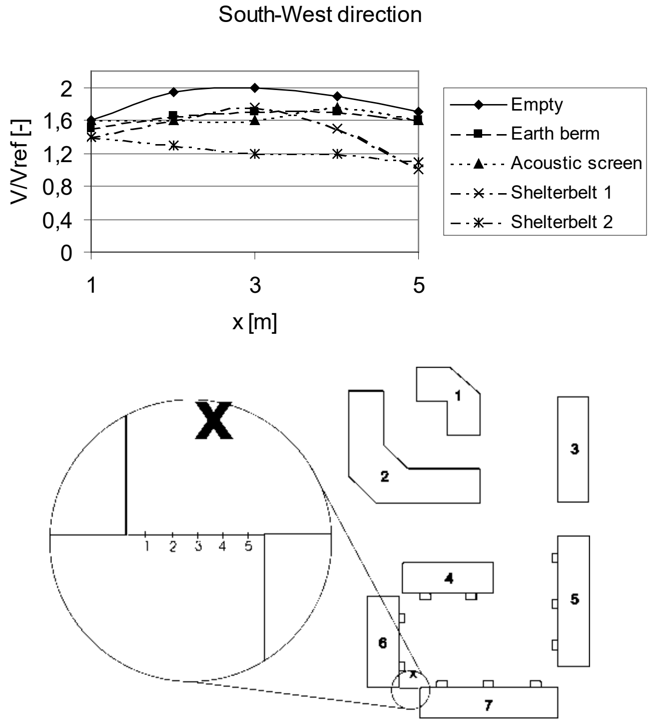

Fig. 11. Distribution of wind speed ratio V/V_o in the passage between buildings 6 and 7 for different windbreaks and south-west wind direction [18]

The best results were obtained for the shelterbelt 2. Additional row of trees in the southwest part of the buildings complex reduces wind speed ratio about 0.6. To check the efficiency of individual shelterbelts in the case of different wind directions, wind speed ratio was determined in a selected point located in the most affected zone (Fig. 12). Location of that point is shown on Figure 11.

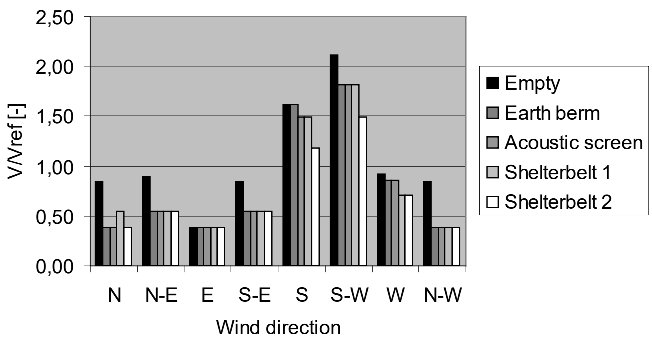

Fig. 12. Wind speed ratio in the analysed point for different wind direction [18]

The evident influence of shelterbelt 2 on wind speed reduction can be observed for almost all wind directions. Only in the case of the west and east winds the effect was relatively small. Shelterbelt 2 consisting of two rows of trees gives the best protection among all considered types of wind screens when wind flow from west and southwest directions. In the corner streams of the upstream buildings wind speed ratio changes from 2 to 1.62.

4. The effect of wind load on conduction heat loss in buildings

One of the factors describing heat exchange on outer surface of building envelopes is wind. In complex urban environments wind speed varies depending on layout of the buildings and their geometric parameters. Therefore, the appropriate estimation of its value in the nearest proximity of a building envelope is critical for energy simulation purpose. Numerical simulation could provide detailed information about wind speed distribution near buildings. In order to illustrate the influence of wind on heat loss, CFD analyses of wind flow around a multifamily building have been made. The obtained results were then used as input data for energy analyses.

The analysed building is a part of a small urban complex located in the suburbs of Warsaw. Figure 13 presents the location of the building.

It is a typical, forty years old, ten floor concrete building with balconies on the western elevation. Thermal properties of external partitions are rather poor, where values of heat conduction coefficient equal 1.14 W/m^{2}K for walls and 2.6 W/m^{2}K for windows. Furthermore, the joints of elements (windows-slab and slab-slab) are imprecise and caused greater heat losses by infiltration.

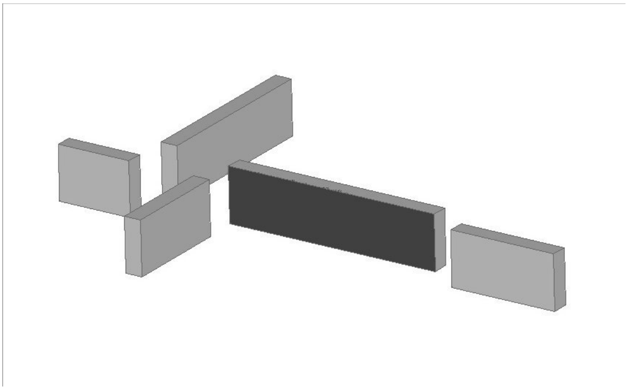

Fig. 13. Prospective model view of the analysed building and its surrounding [19]

As a result of numerical simulation wind speed distribution data around analysed building was obtained. Figure 15 presents zones of different wind speed at 3 m height for west, dominated wind direction. Additionally, the wind speed was estimated in the selected control points at 1m distance from the western wall. The side points were situated at 2 m intervals from the edges; the upper ones at 1.5 m and the bottom ones at 3 m. The location of the control points has been shown in Fig. 14.

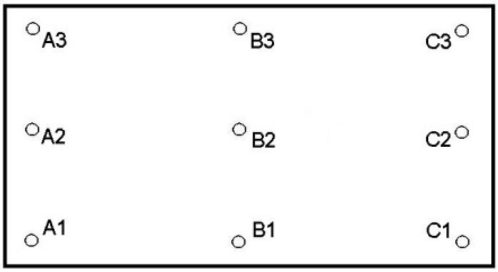

Fig. 14. Control points location [19]

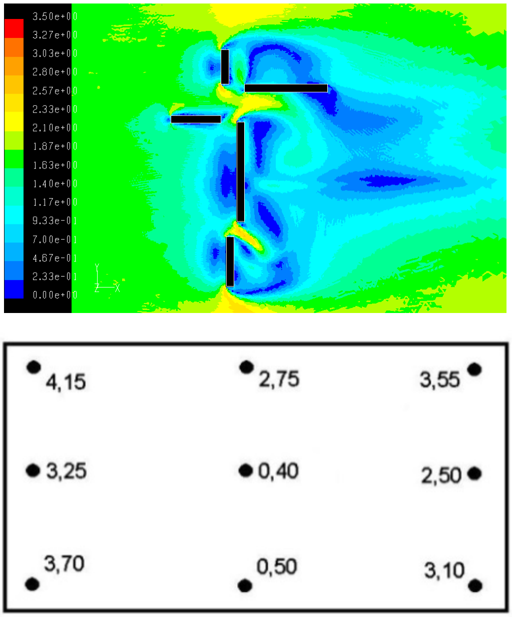

Fig. 15. Flow field and the values of wind speeds [m/s] for west wind direction [19]

In the case of the western flow direction perpendicular orientation of the building reduces the wind flow. The lowest wind speeds occur in the middle of the windward face. Near the corners of the building the wind accelerates. The wind speed ratio V/V_o (the ratio of the mean wind speed V at the 3 m height to the reference wind speed at the same height) reaches 2.5.

The CFD results show considerable differences in wind speed distribution in vicinity of the external wall in a 10-story building. The magnitude of air velocity varies from 0.40 m/s in the central parts of the wall to 4.15 m/s in the top corner Fig. 15).

For the purpose of energy analysis the numerical model has been created with ESP-r (Environmental System Performance) tool [20]. Detailed description of numerical procedure has been discussed in [19].

First, simulations were conducted for the maximum and minimum value of wind speed reported from CFD simulation in the nearest surrounding of the west elevation. Initial calculations showed that the maximum heat flux difference in the middle of the night (the highest temperature difference) is 216 W/m^2 (about 30%) (Fig.16).

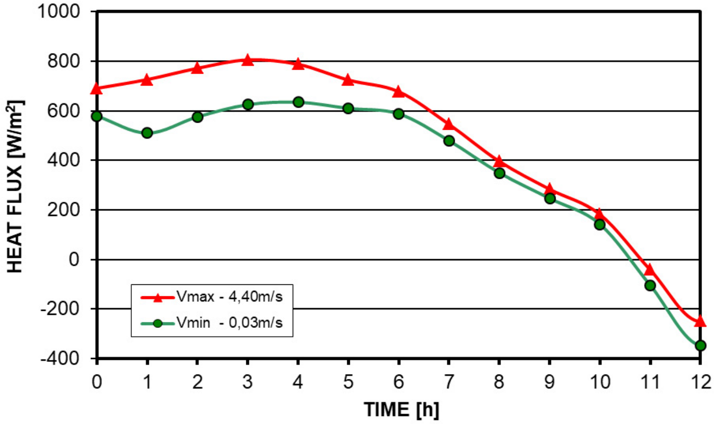

Fig.16. Heat flux for minimum and maximum wind speed from west direction [19]

Subsequently, the conduction heat flux has been calculated for each characteristic point on the elevation. The results for 12 hours are presented in Figures 17-19. They were compared with heat fluxes calculated for wind speed in an open area, estimated on different levels according to wind profile. The assumed winds speed equal 2.39, 3.90 and 4.64 m/s on 1, 2 and 3 levels respectively and are indicated by index V_o.

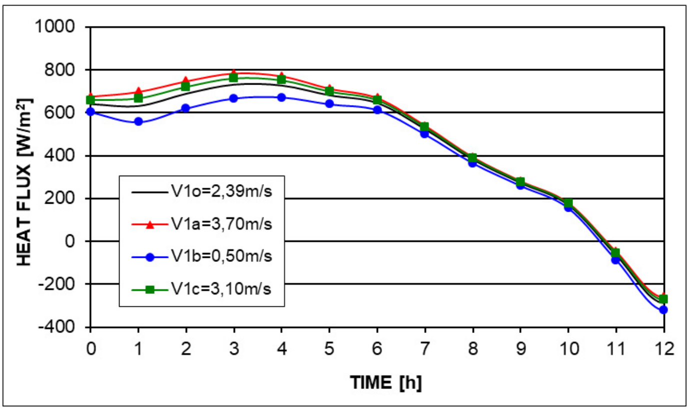

Fig. 17. Heat flux for west wind direction (Fig. 15) and speeds values estimated at points 1A, 1B and 1C compared with initial value 2.39 m/s [19]

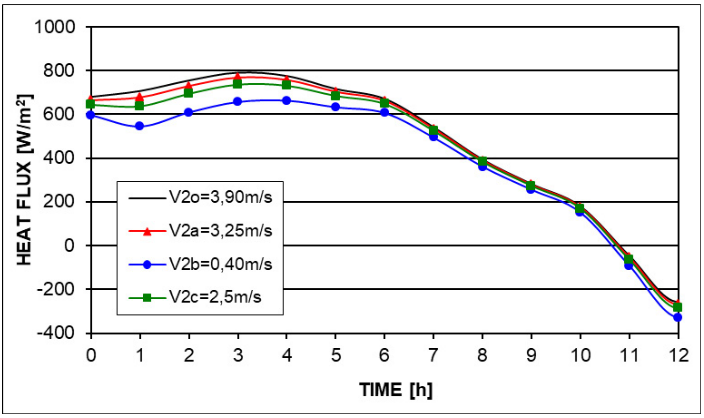

Fig. 18. Heat flux for west wind direction (Fig.15) and speeds values estimated at points 2A, 2B and 2C compared with initial value 3.90 m/s [19]

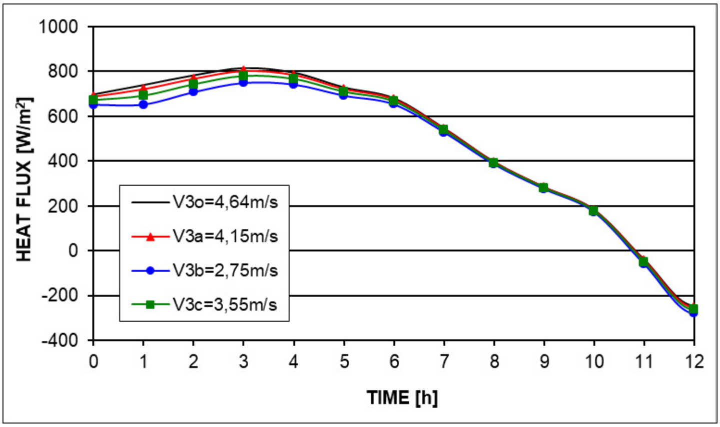

Fig. 19. Heat flux for west wind direction (Fig.15) values estimated at points 3A, 3B and 3C compared with initial value 4.64 m/s [19]

The results for the bottom level, where some local perturbations were detected, show the biggest horizontal differences (Fig. 17). It results from local acceleration or deceleration around the building. In the analysed case, the west wind induces some acceleration especially on the left-hand side of the wall. It caused considerable increase in conduction heat flux on the external surface. On the other hand, the heat losses in the zone located on the middle-low part of the building are much lower (about 25%) than for the zones on the top and the corners. Additionally, the central part of the wall shows the biggest vertical differences in heat flux (Fig. 17-19). Relatively, small differences in wind speed and heat flux (Fig. 19) were reported on the upper level – 1.5 m under the roof edge (about 10%).

5. Summary

The need for favourable wind conditions in a built-up environment is increasingly recognized by the architects and urban planners. Air flow around buildings and its effects are important from the point of view of comfort of people living in their vicinity, as well as the urban ventilation and heat losses in buildings.

Numerical simulations become an increasingly used tool to determine the wind climate. Simulation results provide designers with important information on the influence of buildings on local wind conditions. They allow testing of alternative solutions and, in relation to multi-criteria optimization, searching for solutions which are the most beneficial from the point of view of the adopted assumptions.

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Budownictwo i Architektura 21(3) 2022, 35-50
DOI: 10.35784/bud-arch.2993

Received: 05.06.2022; Revised: 06.10.2022;
Accepted: 11.10.2022; Available online: 31.10.2022

Influence of outdoor advertisements on architecture in the City of Lublin

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Abstract: Polish cities are currently facing an issue of intrusive billboards obstructing the faacades of buildings. While the majority of articles on this subject focus on the negative impact this phenomenon, little attention is drawn to the destructive technical effects the advertisements have on the facades. This article addresses phenomenon of visual pollution examins the influence of based on the example of selected buildings located in Lublin's City Centre. The article analyses the placement of advertising signs, and categorizes of most technical and social problems that it entails. The relation between the occurrence of outdoor advertising and the increase in anti-social behaviour in commercialised space, raised in the article, could be a very important topic for further research. The results of the conducted study reveal that the installation of advertising billboards irreversibly damages the facades of buildings, which is especially visible when the advertisements are removed. The article complements the study on outdoor advertising, drawing attention to one of its little-discussed, technical aspects. Consequently, it may serve as a starting point for further discussion on the subject.

Keywords: billboard, outdoor advertisements, building facades, visual pollution, destructive effect

1. Introduction

Outdoor advertising has evolved considerably over the years, moving from paper signs to luminous screens and interactive LED billboards. Despite the transfer of advertising to the internet, outdoor advertising influences the consumers the most and continues to evolve [1]. The element which plays a significant role in advertisements is colour. Colourful advertisements are read 42% more often than the black and white ones [2]. Colour enhances also human memory [2], which is certainly taken into account in marketing campaigns. At the same time, advertisers began to utilise high building facades to mount advertising billboards and signs to ensure that they reach as many people as possible (Fig. 1). As a result, such advertisements became ever-present in city space, forcing consumers to assimilate the information presented on them [3]. While the entrepreneurs undoubtedly have the right to advertise their products, their activity has visually cluttered the city space since the 1990s [4].

Fig. 1. Advertisements covering the entire facade and roof of a building, 31 1 Maja Street, Lublin. *Source:* Author

The research problem discussed in this article concerns the negative impact of outdoor advertising media, such as billboards, on building facades and their surrounding space. Legal regulations known as the Landscape Act, created in 2015, gave municipalities the opportunity to bring a number of changes to spatial development plans [5]. In other cities, London for example, such regulations have already been in place since 2007 and are precisely defined in The Town and Country Planning (Control of Advertisements) [6]. The problem of excessive presence of billboards in a cityscape has still persisted in 2021. Lublin is currently working on its own draft of this legal act hoping to apply more restrictive regulations to the city centre with a view to improve the appearance of the city. Once the act comes into force, the entrepreneurs will have to remove their advertising billboards, which will significantly improve the esthetics of the city. This removal, however, besides exposing old mounting fittings and accumulated dirt on plaster, will also lead to other problems making it necessary for the entire facades to be renovated.

The aim of this article is to examine Lublin city centre and its downtown area with the focus on the destructive impact of outdoor advertising on building facades. The article presents the extent of irreversal damage the installation of signboards causes to the facades of buildings located in the centre of Lublin. The visual condition of building façades after dismantled advertisements was investigated, as well as what adverse consequences the installation of advertisements on façades entails, such as left-over mounting elements, holes, and damp patches. Furthermore, the article discusses the phenomenon of visual pollution and negative social attitudes caused by an excessive outdoor advertising in the city centre. The problem presented in this article should be considered as an important topic for further research.

1.1. Literature review

For decades, outdoor advertising has troubled the professionals all over the world [7]–[11]. Excessive presence of advertisements in towns and cities has been causing controversies, and it stems from the absence of clear legal regulations. The Landscape Act gave the Polish municipalities the right to amend provisions of local plans and set specific rules concerning the location of advertisements in public space in 2015. To date, 44 municipalities have adopted the Act (1.8% of all municipalities) [12], including Kraków, Gdańsk, Szczecin, and Karpacz. In many others, such attempts were not fully successful. Warsaw, for instance, following the decision of the Supreme Administrative Court from September 2021, became obliged to make necessary changes in the act before it is resubmitted [13]. Meanwhile, Lublin is constantly working on provisions that have been presented in its own draft of such resolution [14]. The provisions concern the central part of the city, which is to be cleared of advertisements within two years from the adoption of the resolution [15], [16].This article complements previous studies by focusing on the physical impact of advertisements placed on building facades. Additionally, the article discusses other problems these advertisements contribute to.

1.2. Characteristics of the study area

Lublin is the capital of Lublin Voivodeship, located in eastern Poland. It has 337 788 inhabitants and the city area covers 147.45 km^2. The population density is 2294.1 persons per km^2. A large group living in Lublin are non-registered students. There are approximately 65 000 students (data from 2021) [23]. The unemployment rate is 5.8% [24]. The number of people registered in lublin has been declining since 1999. The reason for this is suburbanisation. However, the area of Lublin is increasing as it absorbs suburban municipalities. The largest proportion of residents are aged 30-34. Unemployment increased in the late 1990s. Several companies from various industries have their headquarters in Lublin, including the door manufacturer Pol-Skone, the vaccine factory BIOMED and Polfa Lublin, Stock Polska, the pasta factory Lubella, the sweets manufacturer Solidarność, Indykpol, Poland's largest brewery, Perla, and tabacco products manufacturer Zakłady Tytoniowe in Lublin. Most of these companies advertise their products on outdoor signs and billboards. There are 855 vacant advertising boards for rent in Lublin (as of 26 September 2022) [25].

Lublin has been divided into 27 auxiliary areas with the status of districts since 2006 (Fig. 2). Each district has a council and a board and operates on the basis of resolutions. The largest number of registered residents is in the Rury district and the smallest in the Abramowice district, which is also one of the largest districts in the city. The Śródmieście district is in 22nd place in terms of the number of registered residents [26]. The research conducted by Chmielewski Sz. and Chmielewski T. J. for 3 districts in 2013 – Śródmieście, Wieniawa, Czechów Południowy, shows that district Śródmieście had the largest number of advertising spaces, 926 to be precise. For the district of Czechów Południowy it was 518, and for the district of Wieniawa 165 [22]. A considerable number of these spaces are located at intersections and along main streets, where as strong, visual stimuli, they attract the attention of drivers [27], e.g. the intersection of Wojciechowska Street and Kraśnicka Avenue, or Mokrskiego roundabout, where some particularly luminous LED advertisements have been installed. Freestanding billboards significantly impact the commercial zones with mixed-use and industrial facilities such as Węglin, among others.

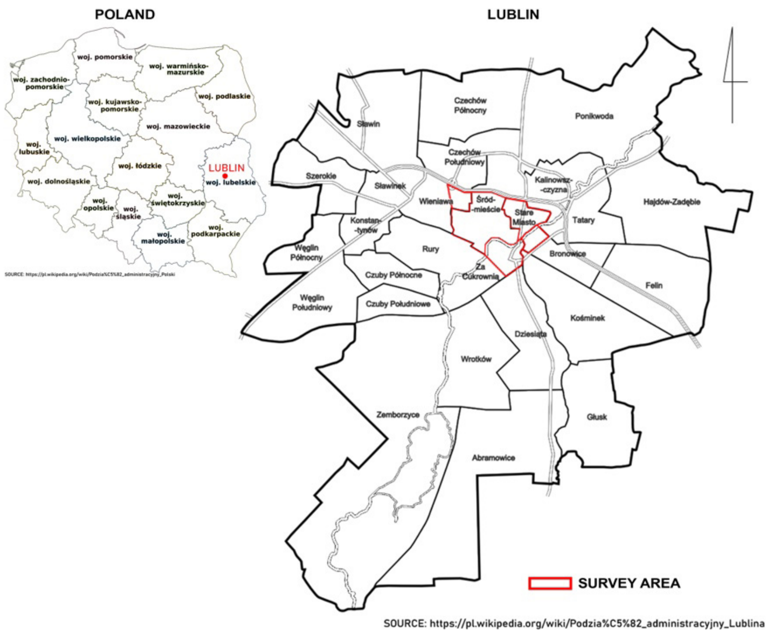

Fig. 2. Location of Lublin in the background of Poland and location of the survey area on the city of Lublin. *Source*: Author; map source: [26], [28]

3. Methodology

Twenty-three locations of billboards in the city centre were selected for the survey – Śródmieście district and parts of Wieniawa, Za Cukrownią, Bronowice, and Stare Miasto districts. The main selection criteria for the Śródmieście district was that this district is covered by a draft resolution of the Lublin City Council on the principles and conditions of placing small architectural objects, billboards, advertising fixtures and fences, their dimensions, quality standards and types of construction materials they may be made of [13]. Buildings that are registered as monuments in Lublin are covered by the Communal Programme for the Care of Monuments [29] and, therefore, the placement of billboards and advertising devices on these buildings requires a building permit, where it is necessary to obtain the consent of the Conservator of Monuments. Coloured advertising signboards, large-format advertisements and free-standing advertising billboards were considered. Free-standing billboards were not examined as they did not interfere with the fabric of the site but were referred to in terms of visual pollution. The second main criterion was the location of the advertisements on the facades of the buildings. The buildings on which the advertisements are located are in close proximity to each other and include residential buildings, shops located on the ground floors of these buildings and services. Another criterion was the mounting elements left behind or visible holes from the removal of signs on the facades of these buildings. Those buildings where the damage was clearly discernible were selected. The overall condition of the space surrounding these buildings was another factor taken into account in the selection process. Factors such as cleanliness and the presence of graffiti was considered. As the inner city district is the first to be covered by the Landscape Act, and where a majority of buildings have large outdoor advertisements, it became the main focus of this study [22]. It was necessary for the survey identify and select buildings showing significant damage from mounted signs or advertising boards. Buildings where it was not possible to clearly determine whether the condition of the facade could have been affected by advertising were not included in the survey. After analysing each street by GNSS and secondly by foot, objects that met the above criteria were selected. The researchers selected 8 streets of the surveyed neighbourhoods that were identified as the most critical due to the destruction of building facades and the amount and size of advertising on the facades. The first step of the research was to categorise the location of advertisements. Freestanding advertising billboards situated at street intersections were not included in the study, as this topic has already been sufficiently addressed in other works [19], [22], [27].

The research material consisted of the author's photographs of the objects and their division according to selected criteria, as well as information obtained from various publications and websites. Also, the measurements of wall cavities resulting from the dismantling of advertisements were taken in January 2022.

4. Results

4.1. Locations of advertisements

Following the field survey, 8 of the most critical sites located in the area of research were observed (Fig. 3). These are the streets and areas were to have the highest grade of visual pollution. In the Śródmieście district, these were mainly Okopowa, Lipowa, and G. Narutowicza, Solidarności Avenue, Nadbystrzycka and Głęboka Streets. In the Old Town on Unii Lubelskiej Avenue, large-format advertising obscured a large area of the buildings' facades, covering them almost entirely. In the Za Cukrownia district, on Fabryczna Street, many colourful advertisements are easily visible from the Downtown district. In the Wieniawa district, there is a view of large-format advertisements attached to the entire facades of multi-family buildings (Fig. 4). This confirms the presence of visual pressure exerted by numerous advertising surfaces on the urban landscape.

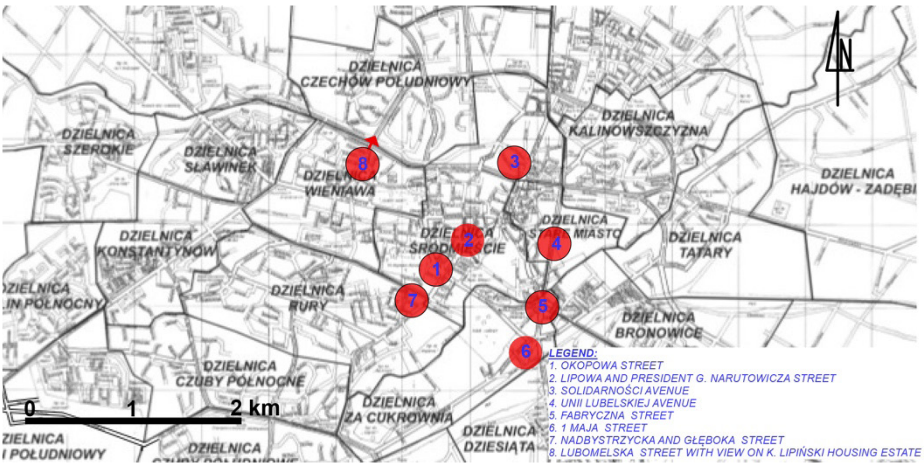

Fig. 3. Illustration showing the sites surveyed and the neighbourhoods where the survey was conducted. *Source*: Author; map source: [26]

Fig. 4. Large billboards placed on walls of residential buildings in K. Lipiński housing estate, view from Lubomelska Street. *Source:* Author

After an analysis, four most common locations for the placement of advertising billboards were selected:

1. Building walls (including railings) – 87%
2. Windows – 39%
3. Roofs – 9%
4. Open space (including intersections) – 13%

The largest number of advertisements was located on walls of building facades; the number of advertisements placed on windows was approximately two times smaller. Advertisements were also mounted on the roofs of some buildings (Fig. 5).

Fig. 5. Advertisements installed on walls and roofs of buildings – 2 and 3 Fabryczna Street and 2 Okopowa Street. *Source:* Author

3.2. Identified problems related to the location of advertising signboards

The condition of the facades of the 23 of surveyed buildings with advertisements turned out to be much worse than of the buildings without advertisements. In many places, especially on Lipowa Street, building facades from which advertisements had previously been removed were left with holes of diameters ranging from 5mm to several centimetres, or remains of mounting elements. The probable reason for this was the change of owners of service premises who mounted and dismounted advertisements of their business (Fig. 6). Two types of damage on building facades caused by advertisements were identified:

[1] Mechanical (mechanical damage of building facades – holes, cracks);

[2] Biological and chemical – transformation of the building substance resulting from permanent dampness (mould, bird droppings).

Fig. 6. Holes in building facades left after demounting advertising signs. *Source:* Author

Further problems included the damage of the advertisements caused by atmospheric factors, such as wind, and visual pollution ehich lead to the contamination of building facades resulting from excessive presence of advertisements.

The survey identified five problems as a consequence of mounting and demounting advertisements, which were classified into the following categories:

1. streaking, mould, and contours of removed advertisements,
2. defects in walls or holes left in building facades,
3. birds,
4. litter,
5. graffiti.

The diagram below shows the ratio of the number of problems encountered to the number of sites surveyed (Fig. 7). The most frequently occurring problem are holes in walls or the reminders of old mounting elements. In 11 of the 23 sites surveyed, this problem was observed, which was 48%. Damp patches, mould, and contours of removed advertisements are also common. It represents 35% of the sites surveyed (8 out of 23 sites surveyed). Graffiti and litter are less frequent in 22%.

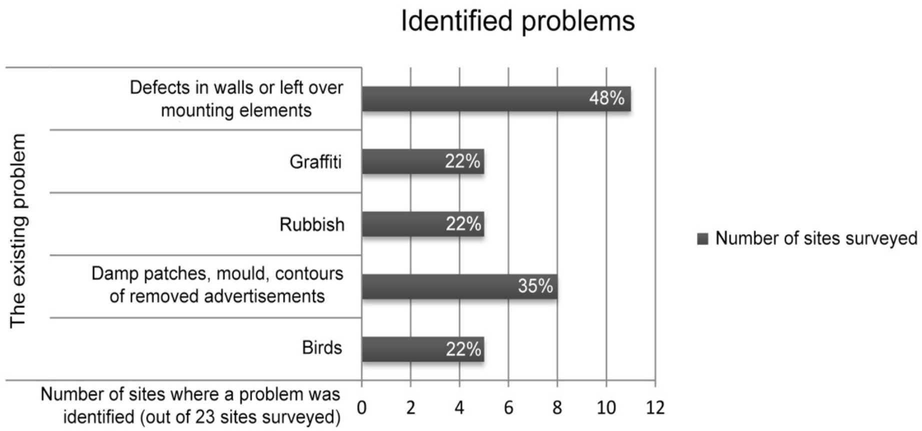

Fig. 7. Identified problems in relation to the sites surveyed. *Source:* Author

Every crack or additional hole allows water to penetrate the underlying layers of the wall, contributing to the degradation of the integrity of the building. Moisture, when retained in the wall, causes cracks that widen in time, creating space where atmospheric dirt deposits. Billboards on buildings were also observed to attract birds, which leave their droppings on walls and pavement below them.

In areas of flashings and the upper edges of advertisements (Fig. 8) it was possible to observe green, black, or grey deposits – microbiological contaminants such as algae and other fungal spores. Not all buildings with installed billboards show fungal contamination: it is influenced, among other things, by the orientation of the facade, therefore facades with billboards located towards the north and east are less exposed to light and more vulnerable to the development of microorganisms. Billboard mounting disrupts the continuity of thermal insulation of walls, which become prone to thermal bridges and required additional protection. On many buildings, the colour of plaster in areas that were previously covered with advertisements was noticeably different from the rest of the facade. There were also other visible, unevenly placed discolorations, such as black smears above and below the billboards and rusty stains caused by poorly fastened billboard mounting elements. The holes left by the dismantled advertisements have not been plastered or painted over, which creates the effect of a perforated wall (Fig. 9). The list of locations of outdoor advertisements and identified problems is provided in Table 1.

a) b)

Fig. 8. a) Algae stains and drips caused by advertisements: 18A Lipowa Street; b) Building facade after removal of advertisements, 45 Chopina Street. *Source:* Author

Fig. 9. The points highlighted in red are holes left after repeated removal of advertising signs, *Source:* Author

Table 1. List of locations of outdoor advertisements and identified problems. *Source:* Authors

No.	Localization	Location of advertisements				Existing problem				
		Wall	Window	Roof	Open space	Birds	Damp patches, mouldy contours	Rubbish	Graffiti	Defects in walls or left over installation elements
1	Building, 18 Lipowa Street 51°14’36.9”N 22°33’11.6”E	x				x	x			
2	Building, 1 Dr J. Sztajana Street 51°14’34.3”N 22°33’12.5”E	x				x	x			x
3	Billboard, Unii Lubelskiej Avenue 51°14’29.6”N 22°34’24.2”E				x			x	x	
4	Billboard, intersection of Głęboka and Nadbystrzycka Street 51°14’20.4”N 22°33’06.5”E				x			x		
5	Building, 1 Nadbystrzycka Street 51°14’20.0”N 22°33’07.1”E	x				x				x
6	Building, 75 Narutowicza Street 51°14’25.5”N 22°33’12.3”E	x					x			x
7	Building, 78A Narutowicza Street 51°14’21.9”N 22°33’10.2”E	x	x						x	x
8	Building, 71 Narutowicza Street 51°14’27.0”N 22°33’13.8”E	x				x	x			x
9	Building, 67 Narutowicza Street 51°14’28.5”N 22°33’15.5”E	x								x
10	Building, 65 Narutowicza Street 51°14’29.2”N 22°33’16.4”E	x	x			x		x		x
11	Building, 45 Chopina Street 51°14’31.3”N 22°33’16.5”E	x	x				x		x	x
12	Building, 19 and 21 Lipowa Street 51°14’33.3”N 22°33’11.5”E	x					x			x
13	Building, 31 Narutowicza Street 51°14’41.0”N 22°33’28.6”E	x					x			
14	Building, 28A Narutowicza Street 51°14’40.0”N 22°33’30.9”E	x						x	x	
15	“Gala” Shopping Mall, 1201 Unii Lubelskiej Avenue 51°14’19.5”N 22°34’22.5”E	x	x							
16	Buildings, 2 and 3 Fabryczna Street 51°14’15.9”N 22°34’20.1”E	x	x	x				x		
17	Building, 29 and 31 1 Maja Street 51°14’06.9”N 22°34’14.0”E	x	x	x			x			x
18	Building, Plac Bychawski 3 51°14’05.5”N 22°34’09.8”E	x							x	x
19	Billboards in front of the Orthodox Cathedral, Tysiąclecia Avenue 51°15’05.6”N 22°34’28.5”E				x					
20	Building, 24C Lubartowska Street 51°15’08.1”N 22°34’04.0”E	x	x							
21	Building, 22c Lubartowska Street 51°15’07.5”N 22°34’04.9”E	x	x							
22	Building, 4 Probostwo Street 51°15’08.7”N 22°33’58.7”E	x	x							
23	View from Lubomelska Street in the direction of the K. Lipiński Housing Estate 51°15’07.8”N 22°33’06.6”E	x								

4.3. Other identified problems

Another aspect that has been observed was a greater tendency to litter in some areas where billboards are present. For instance, at the intersection of Nadbystrzycka and Głęboka Streets, it was possible to notice fragments of advertisements that were torn by wind littering the pavement (Fig. 10). The surroundings of the largest billboard on wheels in Lublin, located on Unii

Lubelskiej Avenue, showed signs suggesting that the place attracted those involved in such as writing graffiti and alcohol consumption: the lawn near this advertisement was covered with empty alcohol bottles and cans (Fig. 11).

Fig. 10. Advertisements torn by the wind at the intersection of Głęboka Street and Nadbystrzycka Street. Source: Author

Fig. 11. Rubbish next to a billboard as a symptom of anti-social behaviours. Unii Lubelskiej Avenue. Source: Author

The impact of advertising on the behaviour of space users requires separate interdisciplinary research. This problem, although only briefly presented in the article, should therefore be treated as an important topic for further research.

5. Discussion

Visual pollution is created not only by outdoor advertising, but also by any eyesoring cabling and infrastructure elements [30]. The management of outdoor advertising with software such as GIS would help control the location of any advertising devices. Researchers Sz. Chmielewski, M. Samulowska, M. Lupa created the Visual Pollution application, which, using mapping and a GIS model, helps determine the level of visual pollution [31]. The authors of this application developed a visual pollution level for Zana Street in Lublin, Rury district.

On the contrary, large advertisements can certainly add character to places with no significant features [17]. This phenomenon has been described by R. T. Wilson and B. D. Till [1], who used the case of the Times Square in New York as an example. Thus, when a place is devoid of any distinctive elements, an installed billboard may become a point of reference. At the same time, however, advertisements are associated with certain environmental problems, which at the time of a climate crisis mustn't be ignored. For instance, the larger the advertisement, the more energy and material is needed to produce it. Another problem concerns the disposal of advertisments.

It has often been stated, that unattractive places encourage vandalism [2], whereas well-maintained places with greenery, no graffiti, and aesthetic rubbish bins, are more likely to remain clean and, in general, inspire different kinds of behaviours. Graffiti found on many billboards can be considered a manifestation of a struggle against advertising. People who place their own messages on outdoor advertisements, regardless of their temporary nature, refuse to accept the one-way flow of advertising messages [32]. Graffiti and advertisements are, in turn, linked to negative social behaviours such as littering. According to a 2008 Danish report on the fight against graffiti, if the incidence of graffiti is reduced, littering can be halved. Litter is a major aesthetic threat to the city. According to the American Public Works Association, litter constitutes to be a threat to public health, safety, and prosperity [2].

Additionally, billboards, which mostly depict material goods, encourage people to keep buying and fuel consumerism [17]. According to the 2021 report published by the Chamber of Commerce of Outdoor Advertising, increasing attention is being paid to eco-friendly advertising solutions [33]. A large part of city space is becoming commercialised, that is, oriented exclusively towards making profit. This phenomenon, however, should not be considered as negative, as long as the needs of people are taken into account [34].

The presented results of the research indicate that advertisements significantly disrupt the structure of facades, which leads to their faster deterioration. The main cause of facade damage are atmospheric phenomena such as rain, wind, frost, and air pollution. Droppings also affect the chemical transformation of the plaster and contribute to other destructive processes [35]. Microbiological contaminants such as algae and other fungal spores, it beeing formed in areas subject to moisture retention [36]. Improper installation of billboards may also result in other types of wall damage such as salt efflorescence, discoloration, peeling or falling off plaster [37]. Thus, part of the profits made by advertisers from such advertisements could be allocated to future facade renovation [12].

6. Conclusions

A city, which is a desireable place to live in, is a clean city. Our first, visual impressions of something can permanently influence our opinion because we judge everything with our eyes.

Although building facades are constantly exposed to atmospheric pollutants, such as dust and exhaust fumes, combined with wind, rain or snow, advertisements contribute to the degradation of facades in a more significant way. This pertains to improperly mounted billboards and signs, which when insufficient gap is left between them and the walls, block the air flow. This eventually leads to the appearance of damp patches and efflorescence. Due to the constant change of service premises owners and their businesses, advertising signboards are changed as well, which makes the building facades subject to repeated damage.

After Lublin adopts its landscape resolution, a number of outdoor advertisements will have to disappear from buildings, leaving facades with defects in plaster, drilled holes and remains of fixtures and fittings. Since such damage is certain to detract from the artistic value of buildings, many of them will require complex renovation. Yet, despite of this fact, adopting the landscape resolution will overall bring more benefits to the city by improving the aesthetic quality of its space.

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ISSN 1899-0665