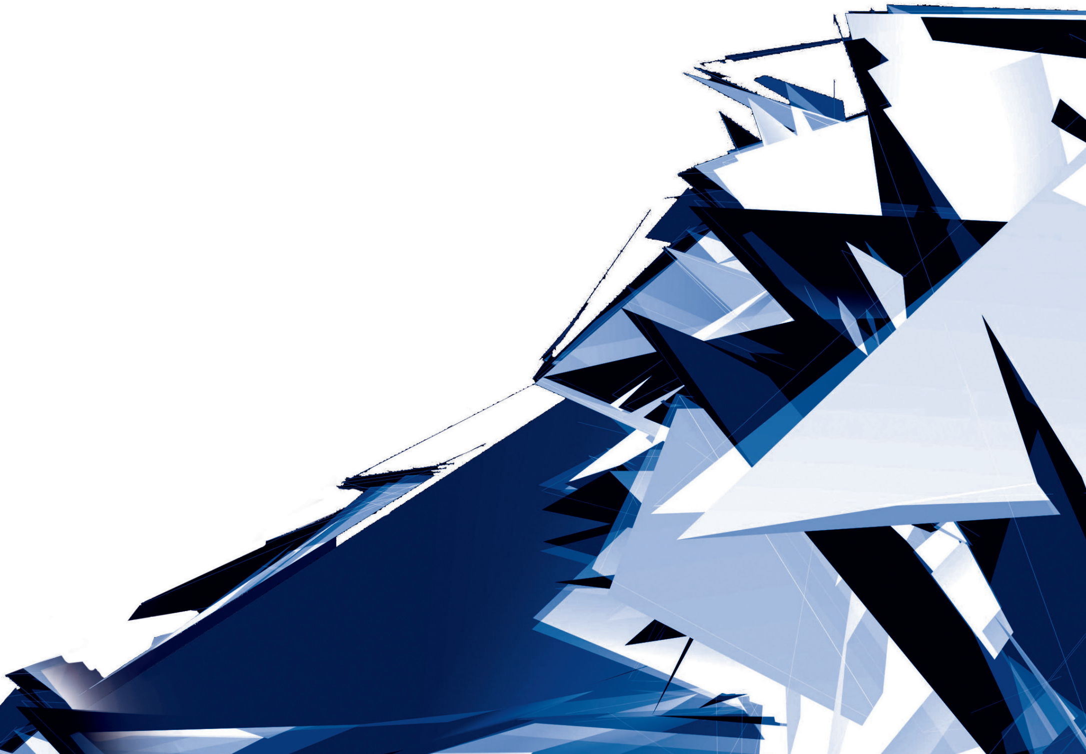
Technical Transactions

Czasopismo Techniczne

Issue 9

Volume 2019 (116)



Online availability
Dostępność online

www.ejournals.eu/Czasopismo-Techniczne
www.biblos.suw.pk.edu.pl
www.czasopismotechniczne.pl

Basic version of each Technical Transactions magazine is its online version
Pierwotną wersją każdego zeszytu Czasopisma Technicznego jest jego wersja online

ISSN 0011-4561
eISSN 2353-737X

Contents

TECHNICAL TRANSACTIONS 9/2019
ARCHITECTURE AND URBAN PLANNING
DOI: 10.4467/2353737XCT.19.091.10873
SUBMISSION OF THE FINAL VERSION: 1/08/2019

Dorota Jopek orcid.org/0000-0003-1504-771X
jopekd@uek.krakow.pl
Department of Regional Economy, Cracow University of Economics

Intelligent urban space as a factor in the development of smart cities

Inteligentna przestrzeń miejska jako element kształtowania rozwoju *Smart Cities*

Abstract

A smart city is a city which, with the use of modern technologies, manages all areas of its functioning in order to optimise results of its development, create new values based on the cultural heritage and natural resources. However, it should be remembered that people create a city; therefore, the technology accompanying the idea of a smart city is only a tool that will be used by society in the process of the development. This paper aims to present the implementation of the objectives of intelligent urban space in the context of the concept of smart growth and the smart city. The author focuses on the analysis of selected approaches to shaping the intelligent city space related to activities within smart environment (blue and green infrastructure) and smart people and lifestyle (activity nodes and local centres). A smart' city creates intelligent space.

Keywords: intelligent space, quality of urban life, smart city, environment, local centres

Streszczenie

Smart City to miasto, które dzięki wykorzystaniu nowoczesnych technologii zarządza wszystkimi dziedzinami funkcjonowania w celu optymalizacji działań, tworzenia nowych wartości oraz pomnażania dóbr i zasobów. Jednak trzeba cały czas mieć na uwadze, że miasto tworzą ludzie, dlatego technologia towarzysząca idei miasta inteligentnego stanowi jedynie „narzędzie", które będzie wykorzystywane przez społeczeństwo. Celem niniejszego opracowania jest przedstawienie realizacji założeń inteligentnej przestrzeni miejskiej w kontekście idei inteligentnego rozwoju (*smart growth*) i inteligentnego miasta (*smart city*). Autorka koncentruje się na analizie wybranych kierunków kształtowania przestrzeni miasta związanych z działaniami w zakresie inteligentnego środowiska (błękitno-zielona infrastruktura) oraz inteligentnego społeczeństwa i stylu życia (węzły aktywności i centra lokalne). Inteligentne miasto tworzy inteligentną przestrzeń.

Słowa kluczowe: inteligentna przestrzeń, jakość życia, *Smart City*, środowisko, lokalne centra

1. Introduction

In the dynamic process of city development, it is important to state that human capital growth does not contribute to meeting the expectations and needs of the growing number of inhabitants, on the contrary, it may make it much more difficult. Scientists try to identify the primary areas in which proper functioning affects the general well-being of a city and its inhabitants. One of the possible solution in this process is the concept of the smart city. Of all its definitions ([7, 8, 10, 13, 14]) there is one which states that "a smart city is a centre which strives to overcome public problems by applying solutions based on information and communication technologies (ICT) as a result of partnership cooperation of interested entities, service providers, at the level of the city's management" [19]. Celewicz also points out that the smart city "should be understood not only as electronic solutions, [and] application systems but also as efficient management of the city and human resources. No machine or artificial intelligence is now so developed to deal with the complex problems of modern metropolises as opposed to bold visionaries and teams of professionals who deal with the improvement of life and solving problems in urban structures around the world" [4, p. 100–108]. Smart City, therefore, is a city which, thanks to the use of modern technologies, manages all areas of its functioning, to optimize its development and create new economic and social values based on cultural heritage and natural resources. However, it should be kept in mind that is people who create a city. The technology accompanying the idea of a smart city is only a "tool" that should be used by smart society in the process of smart – sustainable development. It is difficult to separate the physical form of the city from the social environment because always there is a relation between space and people – its users. People shape space but also space shapes individuals and entire communities with regard to their creativity and their social and aesthetic identity. The quality of human life depends, to a large extent, on the space in which one lives. These dependencies include environmental, social, spatial and economic factors. In analyses and reports concerning smart cities, a set of six primary areas of activity which make up the smart city are most often distinguished; these are governance, economy, mobility, environment, people and living [7, 19].

This paper aims to present the implementation of the objectives of intelligent urban space in the context of the idea of smart growth and the smart city. Based on the literature analysis and in situ research, the author focuses on the analysis of selected approaches to shaping the city space related to activities in the field of an intelligent environment (blue and green infrastructure) and a smart society and lifestyle (activity nodes and local centres).

2. Intelligent urban space

A smart city creates smart space. Although in many studies on the concept of the smart city, the theme of space is either ignored or treated as a secondary issue, in the context of all the above elements defining smart cities, space is an integral element.

The concept of smart space can be defined in a different manner to that which is presented above. According to the original idea of smart cities, smart space can be understood as space in which information technologies are used as tools to improve their functioning. Technology can have an impact on different scales, as it can be applied to individual buildings, individual urban spaces and the whole city. In the field of architecture, we can discuss various types of IT systems for managing high-tech buildings called smart buildings. The main advantage of this type of construction is its efficiency leading to the maximisation of comfort and safety in the use of the building as well as the minimisation of financial and environmental costs associated with the functioning of the building [12, p. 311–322]. Intelligent space is often designed in innovative housing estates or office buildings, which becomes not only *a feature that makes the building more attractive to investors* but is also an example of good design practice combining, for example, commercial investments with ecology. Often, the key aspect of such a space is innovative architecture, for example, architecture that is equipped with multimedia facades[1] which can also perform information and advertising functions. Smart urban spaces may be also related to spaces equipped with innovative design solutions facilitating their functioning or using interactive technologies reacting to user behaviour to, among other, enhance their comfort and safety. The aim of introducing such solutions is often to build a modern image for the given space (and the building itself) and to increase both its commercial and social attractiveness, for example, as a popular, trendy meeting place. Similar objectives can be defined at the planning scale referred to initiatives undertaken in the area of the entire city. A wide range of these activities covers the entirety of the given urban system including those related to technical infrastructure networks, urban transport and the preservation of air quality.

Joanna Bach Głowińska points out that the concept of intelligent space refers to the third[2] dimension of innovation which is related to the cultural mechanism of innovation [1, p. 19]. She also states that this is the space that should be a universal principle determining the set of actions in space. According to Bach Głowińska: "The starting point of the idea' is to understand the needs and feelings of man in contemporary space by defining the mechanism of action of external stimuli necessary for him to undertake the effort of compassion and self-fulfillment, as well as internal conditions of the psychophysical base of creativity" [1, p. 201]. In this context, an important issue is the set of elements of urban space that enhance creativity[3]; this is related to the identification of the needs of city residents. The pyramid of Maslow's hierarchy of needs, interpreted in terms of the spatial aspect, may indicate the basic need for security and accessibility of space affecting comfort and functionality (e.g. in terms of communication). The social and inspirational role of space in shaping creativity, satisfying social and aesthetic needs and self-fulfilment should be placed higher in the hierarchy (Fig. 1).

1 This topic was widely analyzed by Celewicz [3, 4].

2 The first dimension described by Bach Głowińska refers to the original definition, i.e. a new feature that creates economic value. The second dimension is related to the management of the innovation mechanism in various areas.

3 Ch. Landry wrote about the relationship between human creativity and urban space [9].

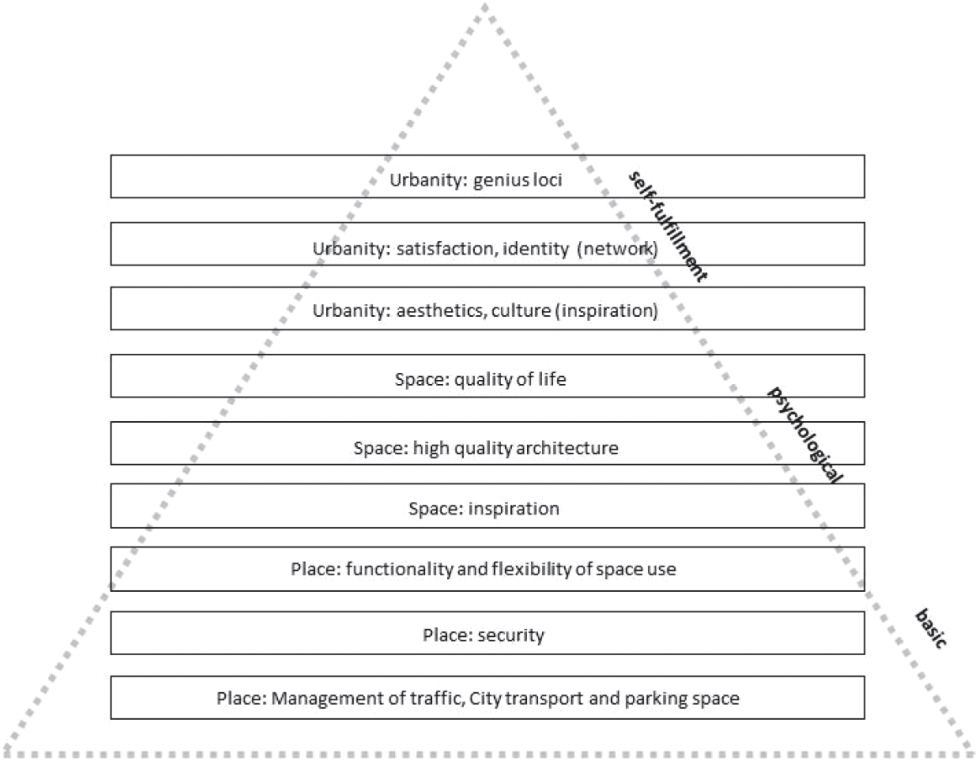


Fig. 1. Hierarchy of social needs in spatial aspects; based on [1, p. 166]

This approach to smart space design corresponds to the principles of smart growth, i.e. the urban and social development of the city, which serves to meet objectives reflecting basic human values. The general objectives and assumptions *are as follows:*

- the need for the functional and social diversification of districts and housing estates, which will also have *a positive* impact on the development of greater activity in these areas;
- the creation of compact developments ensuring greater vitality and a sense of security of the area by increasing the number and activity of people on the street and helping to reduce the costs of technical infrastructure, including transport;
- providing housing for people with different levels of income;
- using existing resources, inter alia, by revitalising urban areas;
- the protection of green open spaces which have significant benefits for the quality of the environment and health;
- the reduction of the environmental and financial costs of the development of the city;
- reducing the need to use individual transport in favour of walking and cycling;
- care for the quality, accessibility and safety of public spaces;
- respect for local identity and traditions, inter alia, in the design of buildings and public spaces;

- striving for dialogue and cooperation with all stakeholders of a given space with regard to decisions concerning its development [16].

The scope of these efforts depends on the inhabitants, authorities and persons responsible for design and investment and must be adapted to the development standards of individual cities. A. Duany, J. Speck and M. Lydon in their handbook [5] presenting activities in the field of the smart growth, indicate the need for action at different scales of design. This range includes the regional scale, the neighbourhood scale, the street scale and the building scale. Within the region, the authors define the development guidelines, the construction of the regional plan and the transport system. The scale of the neighbourhood is determined by the natural context (e.g. greenery, natural corridors), the components of the neighbourhood (e.g. housing density and diversity), and its spatial and functional structure. In the context of the street space, five level of analyses were defined: thoroughfare network and design, public and private streetscape and parking solutions. In the case of buildings, however, the authors identified the types of buildings, the ecological factors of the buildings and a set of possible architectural design patterns. All of these elements of the basic stages of designing the spatial development of the city and must be analysed in the context of local conditions.

3. Cities for people

As previously mentioned, modern cities should offer optimal conditions to meet the needs of their residents. The extent to which the process of providing optimal conditions for living, resting and working is satisfied, determines the quality of life of city dwellers[4]. The quality of urban life should be expressed by a number of criteria that are individually formulated for each city. The criteria should depend on the size of the city and its local development determinants. They should also consist of adjusting the level of the development of the urban infrastructure and the spatial and functional structure of the city to the needs of the inhabitants and their activity.

The objective of the smart city concept is not only the creation of a high quality city space but also the development of an efficient city on an administrative and economic level. Its growth is very strongly focused on the development of a sustainable and innovative city which will be resilient to climate changes. This goal can be achieved through the integration of both modern technologies and social participatory tools in the shaping of the entire process (Fig. 2).

The area of activities within the smart city concept which directly refers to space is the natural environment (smart environment). Here, its objectives should be understood as the sustainable development and management of natural resources in urban areas, which allows maximisation of their current social and economic potential while respecting their values and resources.

---

4 Sociologists point out that the assessment of the functionality and quality of a city's space is assessed by its inhabitants in close relation to the neighbourhood where they live. Public space is produced by society in the process of using, perceiving, valorising and giving appropriate meanings, as described by Prof. B. Jałowiecki among others in the theory of social space production.

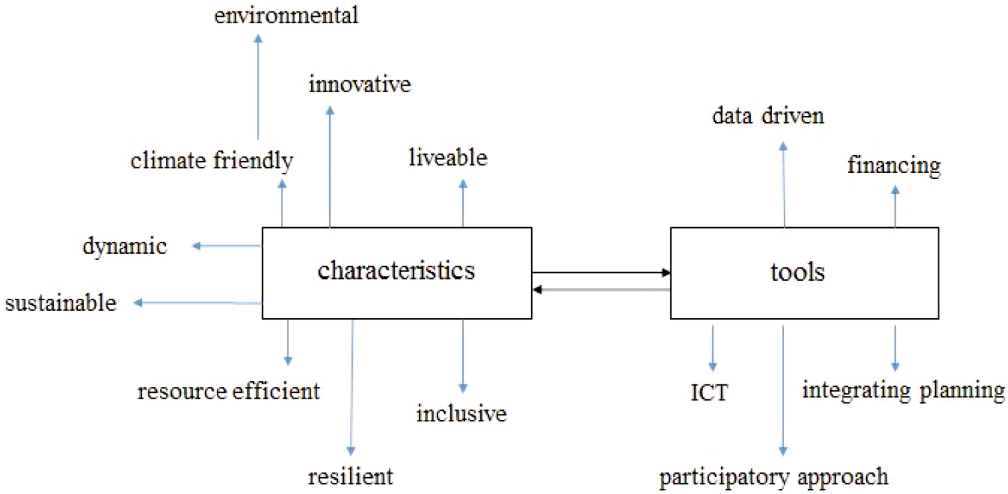


Fig. 2. Characteristics and tools of the smart city concept; based on [6]

Primary areas of activity (defined in the smart city concept) which concern the social layer of the city are Smart People and Smart Living. The development of the city also depends on its inhabitants and their awareness and involvement in the process of implementing projects and initiatives, in this case, the concept of a smart city. Social participation is the main factor influencing the outcome of the changes, people must be willing to use and participate in smart solutions. It is also important to address individual social groups in all actions, as balancing the needs of different interest groups can become the biggest challenge. Activities within individual areas complement each other in many aspects because the quality of the environment has a direct impact not only on the air quality and aesthetics of urban space, but also fosters the positive environment for the physical and mental health of the inhabitants. Research proves that urban areas with a reputation for cohesion, legibility and aesthetics can have a similar regenerative effect on the human body as natural landscapes [15]. Components that co-create these features of urban space are, in environmental terms, the natural layer created by blue and green infrastructure, and in social terms, activity nodes and local centres as generators of identity and human relationships. All these factors influence the sustainability and quality of life in the city.

3.1. Blue and green infrastructure

In the context of the planning and development of blue and green infrastructure, a long-term perspective is important. Its development and maintenance should be included as priority actions in planning documents indicating the manner of shaping and using the entire natural layer of the city, i.e. water and greenery. Moreover, this planning should be integrated and interdisciplinary. Firstly, it is about maintaining a balance between harmony, aesthetics and functionality of the existing or newly created infrastructure. Secondly, for long-term investments, it is necessary to plan with the participation of all stakeholders in a given space: residents, investors, city authorities and experts (including urban planners, economists, sociologists, etc.). Different cognitive perspectives enable the proper planning of infrastructure taking into account the needs of different social groups. The positive impact of the elements of the blue and green infrastructure on the improvement of the quality of urban space and the life of the inhabitants is undeniable due to their aesthetic and/or health values (e.g. air quality, physical activity). Meanwhile, the role of these elements in economic (e.g. tourism, investment attractiveness) and social development (e.g. places of recreation and integration) should be emphasised. Therefore, in the processes of planning and managing urban development, the need to include and intensify activities aimed at increasing the condition and quality of green and water spaces in the city has become indispensable.

Urban space design should include the management of water systems. Depending on the nature of these spaces, water systems can create both natural and artificial elements such as wetlands, ponds and retention basins. These systems are often associated with the surrounding greenery and can also create green connectors that may become corridors between green systems. In addition to their aesthetic value, these systems can be used for rainwater management. In terms of urban planning, design solutions should be implemented which improve the quality of the natural environment and enable rainwater retention within the scope appropriate for the specificity of a given area. This is particularly important in projects conducted in areas with high building intensity, where the percentage of impermeable areas is very high, and in areas constituting the direct environment of watercourses.

Another important element of the blue and green space idea is the development of urban waterfront areas, which should include strategies relating to the management of flood events. These solutions are also becoming increasingly important in the face of climate change, which perhaps constitutes the most important challenge faced by contemporary cities. It should be stressed that actions should be undertaken at different scales and types of space: municipalities, public spaces, districts and housing estate scale, as well as the development of individual private plots. The key issue here is to determine the indicators of development and biologically active area in local spatial development plans, which should correspond to the optimal intensity of development related to the spatial and functional character of a given fragment of the city.

Intelligent urban space is about exploiting the potential to create a multidimensional urban space. Examples in Krakow include the use of a hydrographic network with accompanying greenery as a system of river parks, as well as the creation of green spaces using even the smallest available areas (see Figs. 3 and 4). These activities not only improve the natural environment of the city and rainwater management but also provide an opportunity to create a functional network throughout the city, ensuring better accessibility of green areas to its inhabitants; this in turn brings great social and health benefits[5].

[5] The relationship between health and the urban space is analysed by J. Kobylarczyk.

Fig. 3. Marian Eile`s square as a part of Superpath project in Cracow – source: author

Fig.4. Linear park in Ruczaj area in Cracow – source: author

3.2. Activity nodes and local centres

The city centre is both an important component of the spatial and functional structure of the city and an image of its identity and cultural heritage. The relationship between social needs and the principles of urban planning is very important in the new interpretation of beauty, which is nowadays combined with the need to meet the social and cultural needs of local communities [11, p. 21]. The relationship between spatial organisation and human settlements is of key importance for the development of a sustainable and innovative urban space in contemporary cities. Due to their different locations in the city structure, centres can have different functions and spatial forms that determine the scale of their impact as nodes of social activity; these can be local, urban or metropolitan. It should be noted, however, that from the point of view of improving the quality of the living space of the city's inhabitants, local centres seem to be the most important[6]. They shape not only the arena of their everyday activities, but also build their sense of belonging to the local community. These centres are often existing urban systems which are important public spaces for local communities or have the potential to become such spaces. The aim of activities undertaken in areas of local urban systems is not only to recover the spatial values created by them, but also to strengthen their social and economic role. This is particularly important in the processes of shaping the development of modern cities, where the creation of people-friendly spaces that give the possibility to establish social contact is treated as a priority. Categories of analysis should take into account both spatial, cultural and natural values, as well as functional, social and economic diversity, especially in the context of creating *different* patterns of behaviour and social activity. Apart from local centres, a special role as nodes of activity is fulfilled by large-format commercial, retail, service, commercial and office facilities. However, these are often dominated by commercial functions and are lacking in social functions open to all people who would like to use them.

6 An example of conducted projects aimed at defining local city centres can be found in Warsaw, which is implementing the project: 'Warsaw local centres' [21].

On the basis of the leading functions of urban activity nodes, they can be divided into the following groups:

- social (local centres),
- commercial (shopping centres, shopping malls),
- communication, often in combination with a commercial and service function,
- business, e.g. business parks, technology parks[7],
- scientific, e.g. university campuses,
- cultural and entertainment,
- sports.

As a result of the requirements of different conditions, there is no single universal recipe for successful, high-quality public spaces[8], especially in a case of a local centre or activity node. However, analysis of good practices allows the formulation of general conclusions and recommendations. When strengthening the local development potential, the use of the spatial and social values of city space should be the main elements of each city development, especially in the case of city renewal processes which are based on the existing urban structures. As an example of the local centre development process can be found in Warsaw, which is implementing the project 'Warsaw local centres'. The main goal of this initiative is the creation of the significant public space of the selected city areas which are important for local communities. The design process is conducted with all users of the space who participate in every project stage. The developed design solutions are taken into account when preparing planning documents by the city planning agency (see Fig. 5). That is undoubtedly a prospect of implementing all of the established changes.

Fig. 5. Local spatial management plan of the railway station area of of the district of Wlochy in Warsaw (Koncepcja mpzp rejonu PKP Warszawa Włochy); two design concepts of the local centre with a multifunctional building which will serve as a suburban railway station, a service and office building – source: http://architektura.um.warszawa.pl/sites/default/files/files/PKP_WLOCHY_KONCEPCJA%20tekst.pdf (10.07.2019)

7 The role of technology parks in the city structure is broadly analysed by M. Wdowiarz-Bilska.

8 D. Wantuch- Matla gives a broad perspective of contemporary, high-quality public spaces.

4. Conclusions

In the process of shaping the development of contemporary cities based on the priorities of intelligent and sustainable development, the key factors are social and environmental aspects. No development is possible without people and people need living space that not only create conditions for their physical regeneration but also provide inspiration to create the development. A smart city today should be understood not only as an innovative place based on advanced technology but also as a healthy and aesthetic place that provides its inhabitants with optimal living and working conditions.

The discussed directions of the development of the spatial and functional structure of cities related to the formation of centres and nodes of social activity, and the design and management of resources of blue and green infrastructure are part of the concept of intelligent cities and their development. The aim of the undertaken actions is not only to stop the negative urbanisation processes related to, inter alia, the overflow of buildings on suburban areas but also to shape the development of cities with respect for and enhancement of their values, including natural and cultural values. The above-mentioned activities are certainly not the only remedy for the problems of modern cities, but rather important factors of their development.

Regardless of the ideological assumptions of individual concepts, the most important stage is their implementation and the monitoring of their effects because the provisions contained within the strategic documents will not change anything by themselves.

References

[1] Bach-Głowińska J., *Inteligentna przestrzeń. Trzeci wymiar innowacyjności*, Wolters Kluwer, Warszawa 2014.

[2] Caragliu A., Del Bo Ch., Nijkamp P., *Smart Cities in Europe,* Journal of Urban Technology 18(2)/2011, 65–82.

[3] Celewicz P., *Fasady medialne w aspekcie oddziaływania na otoczenie: wybrane przykłady*, [in:] J. Mikulik, *Inteligentne budynki: nowe możliwości działania*, Wyd. LIBRON, Kraków 2014, 193–213.

[4] Celewicz P., *Smart City Expo World Congress*, Barcelona 2017 – inteligentne rozwiązania przyszłości miast, Środowisko Mieszkaniowe 21/2017, 100–108, [online] http://www.ejournals.eu/housingenvironment/2017/(21)2017/art/10884/(access: 10.06.2019).

[5] Duany A., Speck J., Lydon M., *The Smart Growth Manual,* McGraw Hill, New York 2010.

[6] Eremiaab M., Tomab L., Sanduleac M., *The Smart City Concept in the 21st Century*, Procedia Engineering 181/2017, 12–19, [online] https://doi.org/10.1016/j.proeng.2017.02.357 (access: 20.06.2019).

[7] Giffinger R., Fertner C., Kramar H., Kalasek R., Pichler-Milanovic N., Meijers E., *Smart Cities. Ranking of European medium-sized cities*, Centre for Regional Science, Vienna University of Technology, 2007, [online] http://www.smart-cities.eu/download/smart_cities_final_report.pdf (access: 11.06.2019).

[8] Kobylarczyk J., *Health – promoting nature of the urban space*, SMRLO 2016: Second International Symposium on Stochastic Models in Reliability Engineering, Life Science, and Operations Management, 15–18 February 2016, Beer Sheva, Israel: proceedings/ ed. by Ilia Frenkel, Anatoly Lisnianski – [S.l.]: IEEE, 2016.
[9] Komninos N., *Intelligent Cities and Globalisation of Innovation Networks,* Routledge, London–New York 2008.
[10] Landry Ch., *Kreatywne miasto*, Narodowe Centrum Kultury, Warszawa 2013.
[11] Lombardi P., Giordano S., Farouh H., Yousef W., *Modelling the smart city performance,* Innovation – The European Journal of Social Science Research 25(2)/2012, 137–149.
[12] Niezabitowska E.D., *Metody i techniki badawcze w architekturze*, Wydawnictwo Politechniki Śląskiej, Gliwice 2014.
[13] Mokrzecka, M., *Międzynarodowe systemy certyfikacji LEED, BREEAM i DGNB. Wstępna analiza porównawcza poparta studium przypadku*, Czasopismo Inżynierii Lądowej. Środowiska i Architektury 62(2)/2015.
[14] Neirotti P., De Marco A., Cagliano A., Mangano G., Scorrano F., *Current trends in Smart Cities initiatives: Some stylised facts,* Cities 38/2014, 25–36.
[15] Stawasz D., Sikora-Fernandez D., Turała M., *Koncepcja smart city jako wyznacznik podejmowania decyzji związanych z funkcjonowaniem i rozwojem miasta*, Zeszyty naukowe Uniwersytetu Szczecińskiego 721/2012.
[16] Seresinhe C.I., Preis T., Moat H.S., *Quantifying the Impact of Scenic Environments on Health,* Scientific Reports 5(16899), 11/2015.
[17] Smart Growth, *Network Principles of Smart Growth*, 1998, http://www.smartgrowth.org/about/principles/default.asp (access: 10.06.2019).
[18] Wantuch-Matla D., *Przestrzeń publiczna 2.0. Miasto u progu XXI wieku*, Księży Młyn Dom Wydawniczy, Łódź 2016.
[19] Wdowiarz-Bilska M., *Technopolis – beyond technology park*, IOP Conference Series: Materials Science and Engineering 471/2019, https://iopscience.iop.org/article/10.1088/1757-899X/471/11/112028/pdf (access: 10.06.2019).
[20] Życzkowska K., *Inteligentne przestrzenie komercyjne: Zmienność w czasie generowana poprzez interakcję z użytkownikiem*, [in:] *Miasto nie-miasto: refleksje o mieście jako społeczno-kulturowej hybrydzie*, L. Michałowski, D. Rancew-Sikora, A. Bachórz (eds.), Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk 2010, 267–282.
[21] www.cisco.com/c/dam/en_us/solutions/industries/docs/scc/whitepaper_cisco_scc_idc.pdf (access: 8.05.2019)
[22] http://www.europarl.europa.eu/RegData/etudes/etudes/join/2014/507480/IPOL-ITRE_ET(2014)507480_EN.pdf (access: 8.06.2019)
[23] www. sarp.warszawa.pl/warsztaty-stare/warszawskie-centra-lokalne (access: 1.06.2019)

If you want to quote this article, its proper bibliographic entry is as follow: Jopek D., *Intelligent urban space as a factor in the development of smart cities*, Technical Transactions, Vol. 9/2019, pp. 5–16.

TECHNICAL TRANSACTIONS 9/2019
ARCHITECTURE AND URBAN PLANNING

DOI: 10.4467/2353737XCT.19.092.10874
SUBMISSION OF THE FINAL VERSION: 30/07/2019

Dominika Kuśnierz-Krupa orcid.org/0000-0003-1678-4746
dkusnierz-krupa@pk.edu.pl
Faculty of Architecture, Cracow University of Technology

Lidia Tobiasz
AiAW Design Office Lidia Tobiasz

Synagogues in Podkarpacie – prolegomenon to research

Synagogi Podkarpacia – prolegomena do badań

Abstract

This paper is a prolegomenon to the research on the history, architecture and state of preservation of the synagogues still surviving in the Podkarpacie region. After almost a millennium of Jewish presence in the area, despite wars and the Holocaust, 31 buildings or the ruins of former synagogues have remained until the present. It can be claimed that a Jewish cultural heritage of considerable value has survived in the Podkarpacie region to this day, and therefore requires protection and revalorisation. The paper presents the state of research in this area and an outline of the Jewish history of Podkarpacie, as well as a preliminary description of the preserved synagogues with regards to their origin, functional layout and state of preservation.

Keywords: Podkarpacie region, synagogues, history, state of preservation

Streszczenie

Niniejszy artykuł jest prolegomeną do badań nad historią, architekturą oraz stanem zachowania istniejących jeszcze na terenie Podkarpacia synagog. Z prawie tysiącletniej obecności Żydów na tym terenie, pomimo wojen i zagłady, do dnia dzisiejszego pozostało 31 budynków lub ich ruin, w których kiedyś mieściły się synagogi. Można zatem stwierdzić, że do dzisiaj zasób zabytkowy kultury żydowskiej na Podkarpaciu jest pokaźny, a co za tym idzie, wymagający ochrony i rewaloryzacji. W artykule zaprezentowano stan badań w przedmiotowym obszarze badawczym, zarysowano historię bytności społeczności żydowskiej na Podkarpaciu, a także wstępnie mówiono zachowane synagogi, biorąc pod uwagę okres ich powstania, układ funkcjonalno-przestrzenny oraz stan zachowania.

Słowa kluczowe: Podkarpacie, synagogi, historia, stan zachowania

1. Introduction

The first recorded information about Jewish settlers in Poland can be found in the chronicle of Yehuda ha-Kohen, a German Jew, rabbi, traveller and chronicler, who lived in Mainz in the years 1028–1070. According to that account, there existed a Jewish community in Kiev already in 1018, as well as merchant factories (trading posts) in the then Ruthenian lands: in Volodymyr and Przemyśl [1].

In the next centuries, one could observe the history of Jewish settlement interlocking with the history of Poland. On the one hand, the Jewish community had a singular impact on the development of Polish towns, commerce, crafts, economy, industry and culture; on the other – the Polish Republic offered space in which a unique Jewish parliament functioned for centuries, the phenomenon of Hasidism was born, and Jewish printing houses flourished. From the end of the mediaeval period until the Holocaust the largest diaspora in the world was here, and here beat the heart of Yiddish culture. It was also an area in which there were hardly any cities or towns without Jews, and where synagogue architecture was particularly developed.

This article is an introduction to the research on synagogues in the Podkarpacie region, which constitute tangible evidence of the centuries-long presence of Jews in the area.

2. State of research – studies concerning synagogues in Poland, including Podkarpacie

The first articles devoted to individual synagogues appeared in the 1880s. During the next several decades, information about Polish synagogues only appeared in general publications, most often concerning architecture.

The first mentions and descriptions of Polish synagogues were included in the accounts of the research commission for the history of art in Poland. In the years 1888–1893, Władysław Łuszczkiewicz organised eight science-and-art excursions for students of the Academy of Fine Arts in Krakow around Galicia and the Polish Kingdom in order to research architectural heritage. One such field trip, organised in 1891, in which his students acted as graphic artists, resulted in descriptions, exterior views and sketches of interiors of the Staromiejska and Nowomiejska Synagogues in Rzeszów, and the no longer existing synagogue in Przeworsk. *Sprawozdanie z wycieczki naukowej odbytej w lecie 1891 roku* [2] contained the first detailed descriptions of the interiors in the Staromiejska and Nowomiejska Synagogues, bearing evidence of the uniquely lavish decor in those buildings.

In 1915, a work by A. Grotte entitled *Deutsche, böhmische und polnische Synagogen typen vom XI. bis Anfang des XIX. Jahrhunderts* [3] was published in German, which was an attempt at a synthesis of architecture of German, Czech and Polish synagogues. The study included plans and cross sections of several masonry synagogues from Lesser Poland and Greater Poland, e.g. the Staromiejska and Nowomiejska Synagogues in Rzeszów. These synagogues were also described by J. Pęckowski in his work *History of the city of Rzeszow until the end of the 18th c.* [4]. The issue of

Fig. 1. Synagogue in Cieszanów nowadays (photo by authors)

Polish synagogues was also addressed by R. Krautheimer [5] in the book published in Berlin in 1927 entitled *Mittelalterliche Synagogen*. In the same year an article was published by A. Szyszko--Bohusz *Materiały do architektury bóżnic w Polsce* [6] containing descriptions, photographs and sketches of several synagogues from the then Kieleckie, Lubelskie and Warszawskie Voivodeships. In the studies by R. Krautheimer and A. Szyszko-Bohusz there are no examples from the present-day Podkarpacie region. In their work on the architecture of synagogues, Grotte, Krautheimer and Szyszko-Bohusz put forward the need to establish the type of a synagogue, its development and tried to systematize the architecture of Jewish temples in Poland.

During that period, the architecture of synagogues became the subject of interest for other scientists as well. In 1927, M. Bałaban wrote about defensive synagogues in the eastern borderlands of the Polish Republic [7], and in 1929 he published another study entitled *Zabytki historyczne Żydów w Polsce* [8], in which he attempted to determine the chronology of synagogues in the then Polish territories.

A summary of the then state of knowledge concerning the history and culture of Polish Jews was included in the joint publication from 1932, entitled *Żydzi w Polsce Odrodzonej* [9]. The study contains articles on the subject of Jewish art and synagogue architecture. In 1923 the Unit of Polish Architecture (ZAP) was established at the Warsaw Polytechnic, under the supervision of Prof. O. Sosnowski, and in 1929 the Central Office of Monument Inventorying (CBIZ). The ZAP commenced work on inventorying synagogues and broader research of Jewish art, in which an art historian and photographer, S. Zajczyk, played the main part [10]. He was also the author of an article on the architecture of Baroque masonry synagogues in Poland, published in 1933. In his article he draws attention to 9-square synagogues built in Lesser Poland at the beginning of the 17th and 18th centuries. Besides characterising the basic features of their architecture, Zajczyk also identified and described two types of 9-square Jewish temples.

Fig. 2. Synagogue in Dębica nowadays (photo by authors)

Before 1939, in the course of the research work in ZAP and CBIZ, over thirty synagogues located in the lands of the 2nd Republic were inventoried and photographed.

In the years 1939–1944, Germans murdered Jews and destroyed almost all the monuments of their culture. Wooden synagogues were burnt; the majority of masonry synagogues with their lavish furnishings were demolished. In 1944, Germans burnt down the Unit of Polish Architecture. Its employees managed to save some materials, which, in 1946, were returned to the rebuilt Faculty of Architecture at the Warsaw Polytechnic. Currently they are in the collection of Art Institute of the Polish Academy of Sciences in Warsaw. The collections of ZAP and of the Art Institute of PAS became the basis of the architectonic and photographic documentation for the first book by Maria and Kazimierz Piechotka, *Bóżnice drewniane*, published in Warsaw in 1957 [11]. The book was supplemented and expanded, and then published in 1997 under a new title: *Bramy Nieba. Bóżnice drewniane na ziemiach dawnej Rzeczypospolitej* [12]. In the quoted studies, the authors demonstrate that wooden synagogues were unique phenomena among spatial and construction solutions, especially as far as carpentry was concerned. Polychromes in wooden synagogues were also a rare, practically unique phenomenon.

In 1990, P. Burchard published a book entitled *Mementos and monuments of Jewish culture in Poland* [13], which was the first 'catalogue' of monuments of Jewish culture (synagogues, qahal houses, cemeteries, monuments and memorial plaques) that can be found in Poland. The author included much information about synagogues from the Podkarpacie region, e.g. about the synagogues in Brzostek, Dębica, Dukla, Lesko, Rymanów, Sanok, Ustrzyki Dolne, Cieszanów, Jarosław, Medyka, Przemyśl, Radymno, Stary Dzików, Wielkie Oczy, Czudec, Kolbuszowa, Łańcut, Niebylec, Sokołów Małopolski, Strzyżów and two synagogues in Rzeszów.

Ne of the most important books concerning masonry synagogues is the volume by M. and K. Piechotka *Bramy Nieba. Bóżnice drewniane na ziemiach dawnej Rzeczypospolitej*, published in Warsaw in 1999 [14]. By showing the phenomena that influenced the architecture of synagogues, as well as in-depth studies of the history of Jews in Poland, the book explains the origins and development of synagogue architecture in Polish territories. Valuable elements of the book are archive photographs, inventories, descriptions and origins of 82 synagogues erected between the 16th and the beginning of the 20th century. In the chapter devoted to the synagogues from the 16th and the first half of the 17th century, we can find information about the Staromiejska Synagogue in Rzeszów; in the chapter 'Synagogues from the second half of the 17th century and the beginning of the 18th century' there is information concerning the Nowomiejska Synagogue in Rzeszów, and in the chapter 'Synagogues from the 18th and the beginning of the 19th century' one can find descriptions, inventory sketches and photographs of the synagogues in Łańcut, Rymanów and Lesko. In the final chapter, devoted to synagogues

Fig. 3. Ruins of synagogue in Dukla nowadays (photo by authors)

from the 19th and the beginning of the 20th century, there are archive photos of the synagogues in Wielkie Oczy, Radymno and the Scheinbach Synagogue in Przemyśl.

Another important title is the book *Cmentarze żydowski, synagogi i domy modlitwy w Polsce w latach 1944–1966 (wybór materiałów)* written by K. Urban and published in 2006 [15]. It contains a large selection of documents depicting the efforts made by the Congregation of the Jewish Faith and the Central Jewish Committee in Poland in order to preserve the Jewish cultural heritage remaining in Poland after World War II. The selection of documents was preceded by a brief historical outline on the people of the Jewish faith in Poland in the years 1945–1966. The study includes a list of synagogues, houses of prayer and cemeteries in Rzeszów Voivodeship, as well as materials relating the post-war history of the synagogues in Rzeszów, Przemyśl, Jarosław, Lesko, Nisko and Dębica.

While analysing the state of knowledge concerning synagogues in the present-day Podkarpackie Voivodeship, one has to mention that so far there have been no scientific publications addressing the issue thoroughly.

Writing about the state of research on the Polish synagogue architecture with a particular stress on the Podkarpacie region, one has to mention such source material as the Monument Cards. As far back as the 1950s the National Monument Conservation Laboratories commenced the first research and inventory of the most valuable buildings of former synagogues or their ruins. Most frequently, the work was conducted in order to rebuild and

Fig. 4. Synagogue in Łańcut nowadays (photo by authors)

adapt them to new functions. Nowadays, identification cards of architectural monuments and their former equivalents, so called 'green' information cards, found in the Archive of the Voivodeship Monument Protection Office in Przemyśl and its branch archives, constitute an extremely important source of information concerning particular synagogues, and especially their post-war fate.

In the context of current considerations popular-scientific publications prepared by scientists and popularisers of the history and culture of Polish Jews are also worth researching. The first to be mentioned here is the book *Żydzi w Podkarpackiem* written by A. Potocki [16], a historian who studied the history of the Jewish community in Podkarpacie. There, the author presented the history of Jews inhabiting the area between the Vistula and the San River. He also described the history of Jews in the Bieszczady region in the book *Bieszczadzkie judaica, od Sanoka po Sianki* [17], and of those in Rymanów in the publication *Żydzi rymanowscy* [18].

Much valuable information concerning the history of Jewish communities, synagogues and Jewish cemeteries in Rzeszów can be found in the book *Tamten Rzeszów...* by F. Kotula [19]. Also W. Hennig devoted one chapter in his book *Rzeszowski alfabet* to Jewish temples and prayer houses in Rzeszów [20].

3. Jews in the Podkarpacie Region

In the times of the 1st Polish Republic, the Podkarpackie Voivodeship comprised the south--east area of pre-partition Lesser Poland (parts of the then Kraków, Sandomierz and Lubelskie Voivodeships) and the western part of Red Ruthenia (mainly Ruthenian Voivodeship and a section of Belz Voivodeship). After the partitions, the lands of the present-day Podkarpackie Voivodeship were under the Austrian occupation in the Kingdom of Galicia and Lodomeria (constituting the middle part of Galicia at the time), and a small part was incorporated in the Kingdom of Poland under the Russian occupation. After Poland regained independence in 1918, it was the borderline between Lviv Voivodeship (major part with Rzeszów), Kraków Voivodeship (west part) and Lubelskie Voivodeship (northern outskirts). In the years 1939–1941, a demarcation line between Nazi Germany and Soviet Russia ran across the territory. After World War II, Rzeszow Voivodeship was established for the first time in the history of Poland. Although initially, in the years 1944–1951, almost the entire Ustrzyki County (nowadays Bieszczady County) used to still belong to the Soviet Union, in 1951 it was finally incorporated in Rzeszow Voivodeship. The next post-war administrative division of Poland in 1975 resulted in the area being split into four voivodeships: Tarnobrzeg, Krosno, Przemyśl and Rzeszów (small). The lands were merged again (Przemyśl and Rzeszów Voivodeships, and parts of Krosno, Tarnobrzeg and Tarnow Voivodeships) within the current borders of Podkarpackie Voivodeship on 1 January 1999. At present the voivodeship covers an area of 17 845.76 km^2 and has a population of 2.13 million inhabitants [21].

From the historical perspective, Podkarpacie was the east part of Lesser Poland under the strong influence of the cultural centre in Kraków, and the equally significant (especially in the 19th century) impact of Lviv.

Fig. 5. Synagogue in Medyka nowadays (photo by authors)

According to the population count from 1870, in 74 county towns of Galicia people of the Roman-Catholic faith constituted 40.8%, the Greek-Catholic 15.7%, Evangelical 1.1% of the overall population; Jews constituted 42.2% [22]. Jews lived both in smaller towns and bigger cities. In 27 towns of Western Galicia Jews constituted 35% of inhabitants [22, p. 54]. Towards the end of the 19th century, in Dębica, Dukla and Tarnobrzeg the number of Jews exceeded 80%. In many towns they constituted more than half the number of inhabitants (Cieszanów, Kolbuszowa, Lesko, Lutowiska, Niebylec, Przeworsk, Rzeszów, Sanok and Wielkie Oczy) [16, p. 15].

The most important Jewish centres in Podkarpacie were such cities as Jarosław, Łańcut, Przemyśl and Rzeszów, but also towns such as Leżajsk, Rymanów and Sieniawa where the Chasidim movement, which usually avoided large cultural centres, could develop. Sessions of the Jewish parliament, so called the Sejm of Four Lands (from 1580 to 1764) were held in Jarosław (alternately with Lublin). The town then served as an informal "capital" of Polish Jews [23].

That very well organised social and religious community was annihilated by the Holocaust and its aftermath. Synagogues, prayer houses and cemeteries shared the fate of the people. After the war, in the absence of Jews, unused and abandoned synagogues fell into ruin. Nevertheless, for many years they still were significant elements in the landscape of Polish towns. In the Podkarpacie area several dozen synagogues and numerous Jewish cemeteries have survived until today.

4. Synagogues in Podkarpacie – general remarks

Despite wars and annihilation, after almost a thousand-year-long presence of Jews in Podkarpackie Voivodeship, 31 buildings or their ruins that once housed synagogues have remained until today. The oldest in the area – the Staromiejska synagogue in Rzeszów – was built around 1610 [24, 25]. In the first half of the 18th century three synagogues were built, which have survived until the present: the Nowomiejska synagogue in Rzeszów (1712), and synagogues in Rymanów (1700–1725) and in Lesko (1725–1750) [14, p. 408]. The second half of the 18th century is represented by the synagogues in Dukla (after 1758), Łańcut (1761), Strzyżów, the Nowomiejska synagogue in Dębica (2nd half of the 18th c.) and in Czudec (1795?) [26]. In the first half of the 19th century synagogues were built: the Big in Jarosław (1811), in Ustrzyki Dolne (1st half of the 19th c.); in the second half of the 19th century: in Kolbuszowa (after 1850), in Tarnobrzeg (1870), in Lutowiska (2nd half of the 19th c.), in Cieszanów (1889), Zasańska in Przemyśl (1892), in Nisko (end of the 19th c.), in Stary Dzików (end of the 19th c.), *Jad Charuzim* in Sanok (1897) and in Brzostek (before 1900) [16, p. 31]. In the first half of the 20th century (until 1939), the following synagogues were erected: the Small in Jarosław (1900), in Sokołów Małopolski (1904), in Niebylec (1905?), in Błażowa (after 1907), in Radymno (beginning of the 20th c.), the New (a.k.a. Scheinbach's) in Przemyśl (1918), in Medyka (beginning of the 20th c.), in Zaklików (beginning of the 20th c.), *Jad Charuzim* in Jarosław (1912), Sadogórska (a.k.a. Small) in Sanok (1924) and in Wielkie Oczy (1927) [16, s. 198].

In the 16th century and the first half of the 17th century, the period known as the Golden Age of Polish Jews, there occurred a synagogue building boom. The functional-spatial programme for synagogues (relations between the main room, the vestibule and the prayer room for women) was established, and all the layouts for the main room in masonry synagogues were formed: one-nave rooms on the rectangular plan, clear span rooms with the plan resembling a square, rooms with the bimah-support and nine-square rooms [14, p. 113].

Exceptional and original solutions were rooms with the bimah-support, where the bimah was surrounded by four columns standing on a rectangular dais, which were tied by arcades at the top into one massive column supporting the ceiling. The oldest rooms with the bimah--support that survived until the last war could be found in the following synagogues: the Old in Przemyśl (1592–1594), in Tarnów (the 16th–17th century) and Staromiejska in Rzeszów (1610). Those three synagogues were built at the same time (the turn of the 16th and 17th c.) and relatively close to one another, near the border between Lesser Poland and Red Ruthenia (nowadays Podkarpackie Voivodeship, Tarnów – Lesser Poland Voivodeship). The Old Synagogue in Przemyśl was badly damaged during the war and in 1956 it was demolished. The synagogue in Tarnów was burnt by the Germans in November 1939. In 1942, the ruins were dismantled, so that only the bimah was left which was put under conservation protection after the war. The Staromiejska Synagogue in Rzeszów, which was the only one of the three oldest synagogues with the bimah-support in Poland to have survived World War II, was restored yet the post-war activities and, primarily, its adaptation to serve as an archive resulted in the loss of its unique interior. In the area of present-day Podkarpacie there used to be two synagogues with the bimah-support from the turn of the 17th and 18th century, which were destroyed during World War II: in Nowy Żmigród and Przeworsk [14, p. 267 and 274]. Three buildings representing the 18th-century synagogues with the bimah-support: in Rymanów (1700–1725), Dukla (2nd half of the 18th c.) and Łańcut (1761) have been preserved within the discussed area. Unfortunately, the current bimah in the synagogue in Rymanów comes from the time of its reconstruction at the end of the 19th century; while only perimeter walls have remained from the synagogue in Dukla. The best preserved and the only example of a synagogue with the bimah-support from the period is the synagogue in Łańcut (1761).

During the 1630s, a new type of spatial solution in a synagogue was created – with the so-called nine-square room. Two types of solutions were used in such synagogues: rooms with squares of equal size and rooms with the smaller central square. The layout was still popular in the 18th and 19th century. An example of a room with an identical arrangement of columns dividing the space into nine squares of the same size is the Nowomiejska Synagogue in Dębica (2nd half of the 18th c.) Another example of a nine-square room with all the squares of the same size is the main prayer room in the Big Synagogue in Jarosław (1811). Two examples of nine-square rooms with a smaller central square have been preserved in Podkarpackie Voivodeship: the Nowomiejska Synagogue in Rzeszów (1705–1712) and the synagogue in Strzyżów. The Nowomiejska Synagogue, rebuilt and converted in the years 1954–1963 into the BWA art gallery, lost its former shape. The synagogue in Strzyżów, despite post-war

Fig. 6. Synagogue in Niebylec nowadays (photo by authors)

modernisation and adaptation to serve as a library, has retained the exterior and interior features of synagogue architecture.

After the fall of the Polish Republic, the architecture of the synagogues built in its former territories began to lose its homogeneous character developed throughout the 16th–18th century. In the 19th century, the process of economic, social and cultural stratification as well as religious differences among Galician Jews became more acute. The form and functional programme of synagogues were affected primarily by religious dissent. In the 1st half of the 19th century in Galicia a decided majority of Jews were supporters of the traditional Orthodox Judaism. The so called lengthwise arrangement already used in the 17th–18th century, with the main room preceded by a vestibule in the west and with the prayer room for women on the first floor, became popular in small synagogues with a traditional layout, commonly built in small towns in Galicia [14, p. 425].

In present-day Podkarpackie Voivodeship there have survived to a varying degree sixteen buildings of former synagogues erected in the 19th and at the beginning of the 20th c., with a traditional layout, in which the lengthwise arrangement was applied (Jarosław (Mała), Ustrzyki Dolne, Kolbuszowa, Tarnobrzeg, Przemyśl (Zasańska), Nisko, Stary Dzików, Lutowiska, Brzostek, Sokołów Małopolski, Niebylec, Błażowa, Medyka, Zaklików, Radymno, Wielkie Oczy); one in which the central arrangement was used (Cieszanów); two progressive synagogues (Scheinbach's and Zasańska in Przemyśl) and three founded by the *Jad Charuzim* association (Sanok, Jarosław, and Zasańska in Przemyśl).

Nowadays there are no Jewish communities within the Podkarpackie Voivodeship. The only functioning one, though only occasionally during pilgrimages of the Chasidim to the grave of tzaddiks, is the synagogue in Rymanów. The other surviving buildings, which once used to house synagogues, acquired various functions. The oldest – the Staromiejska Synagogue in Rzeszów – stands empty, after it had been abandoned by the Voivodeship State Archive. Only one synagogue in the area documents the Jewish heritage no longer as a working temple, but as a museum with restored interiors and a collection of Judaica (Łańcut); in two there are art galleries (Lesko and the Nowomiejska Synagogue in Rzeszów); several were converted into libraries (Czudec, Strzyżów, Niebylec, Ustrzyki Dolne, Tarnobrzeg, Wielkie Oczy), a museum (Kolbuszowa), centres of culture (Sokołów Małopolski, Wielkie Oczy), a school (Big Synagogue in Jarosław), department stores (Dębica, Radymno, Nisko, Zaklików) and an educational care facility (Błażowa).

The research shows that many post-war adaptations, deliberately or not, destroyed details connected to their former function and significantly transformed those objects, so that they lost their synagogue character. Seven among the abovementioned buildings underwent such transformations: the synagogue in Ustrzyki Dolne (converted into a library), the synagogue in Nisko (adapted to serve commercial and service functions), the synagogue of the *Jad Charuzim* association in Sanok (converted to serve housing and service functions); the synagogue in Sokołów Małopolski (rebuilt and expanded, it currently houses the Municipal Culture and Leisure Centre); the synagogue in Błażowa (refurbished and adapted to serve as an educational care centre); the synagogue in Radymno (adapted, houses a bottling plant); the synagogue in Zaklików (adapted to serve commercial functions).

Another important group consisted of buildings which survived World War II but are currently in ruins: the synagogue in Dukla (18th c.); the synagogue in Medyka; the synagoga in Stary Dzików and the synagoga in Lutowiska. Those four roofless buildings are unprotected and doomed to extinction.

Recently, owing to the efforts of local governments, associations and foundations, three former synagogues have been restored in the area of present-day Podkarpacie. Among the few is the synagogue in Rymanow. It is the first project to rebuild a synagogue for religious purposes in post-war Poland. It is to serve the Chasidim making a pilgrimage to the grave of tzaddik Menachem Mendel, as well as a centre for education and dialogue between religions. The reconstruction of the synagogue and frequent visits of the Chasidim from the United States and Israel, who can again pray in the house of their ancestors and spiritual leaders, made the town resurface in the awareness of the Jewish community worldwide.

The second example is the rebuilt synagogue in Wielkie Oczy, which at the beginning of the 1990s was still in ruins. It was then that local cultural organisations began to cooperate with the parish in Wielkie Oczy and descendants of the Jewish community in the village, in order to carry out a renovation of the synagogue and its adaptation to a centre of culture and a library. In 16 June 2013, the renovated building of the former synagogue in Wielkie Oczy was officially opened. An Exhibition Room was opened in the restored synagogue, where original objects were collected from the times when Jews constituted a third of the town's

Fig. 7. Synagogue in Rymanów nowadays (photo by authors)

population as well as Judaica bringing visitors closer to the Jewish culture. The Exhibition Room with the entire synagogue building arouse more and more interest among tourists from Poland and abroad, whose growing numbers visit Wielkie Oczy.

The third example in Podkarpackie Voivodeship is the synagogue in Cieszanow. Since the mid-1990s the building was left abandoned. In 2015, it was saved by a complete refurbishment carried out by the town authorities under conservation supervision and preserving the former functional division. A day-care facility for Senior Citizens was opened in the former synagogue in 2017.

Seven more buildings of former synagogues are waiting to be restored and used again. These are: Staromiejska in Rzeszów, Zasańska in Przemyśl, the New (a.k.a. Scheinbach's) in Przemyśl, the *Jad Charuzim* Synagogue and the Small Synagogue in Jarosław, the Sadogórska (a.k.a. the Small) in Sanok, and the synagogue in Brzostek.

Four buildings are in ruins, deprived of roofs, unprotected, and doomed to extinction; they are the synagogues in Dukla, Medyka, Stary Dzików and Lutowiska.

5. Conclusion

Podkarpacie, formerly known as Galicia, is a voivodeship rich in monuments of Jewish culture. Among the most important Jewish centres in Podkarpacie were such cities as Jarosław, Łańcut, Przemyśl or Rzeszów, but also towns such as Leżajsk, Rymanów and Sieniawa where the Chasidim movement, which usually avoided large cultural centres, could develop. Sessions of the Jewish parliament, so called the Sejm of Four Lands (from 1580 to 1764) were held in Jarosław (alternately with Lublin). Then the town served as an informal "capital" of Polish Jews. That perfectly organised social and religious community was annihilated by the Holocaust and its aftermath. Synagogues, prayer houses and cemeteries shared the fate of the people.

Despite immense war losses, the cultural heritage of Jews who once inhabited the Polish territories constitutes a unique phenomenon on a global scale. Unfortunately, the pre-war beauty and lavish décor of synagogues in Podkarpacie is known only from descriptions, reminiscences and pre-war photos. The way of building synagogues, which developed in Polish territories including the Podkarpacie region (synagogues with the bimah-support), is a unique phenomenon not encountered in other countries. Thus, any elements of Jewish heritage that have survived are even more precious. The buildings of former synagogues, even though they may have lost their function and characteristic architectonic features, have not ceased to be valuable evidence of the centuries-long presence of Jews in those towns.

Poland was always a multi-ethnic and culturally diversified country. That variety can be restored in the social awareness to a certain extent, e.g. by restoring synagogues and uncovering what has been concealed for years, also for the lack of knowledge or attention on the part of local communities. Podkarpacie is certainly an area abounding in post-Jewish monuments. Among the most valuable objects located in this voivodeship are: the Staromiejska and Nowomiejska Synagogues in Rzeszów, the synagogues in Lesko, in Rymanów and in Łańcut.

It should be noticed that despite such a large number of preserved monuments representing Jewish cultural heritage, neither in Podkarpacie nor in its capital, Rzeszów, can one find a place that could serve as a Jewish cultural and historical centre and, at the same time, would be a venue where the two milieus separated for long years could finally meet. The best object to be adapted to serve such a function seems to be the abandoned Staromiejska Synagogue in Rzeszów which, as the only one among the oldest temples with the bimah-support, has survived until today.

References

[1] Schiper I., *Rozwój ludności żydowskiej na ziemiach dawnej Rzeczypospolitej,* [in:] *Żydzi w Polsce Odrodzonej. Działalność społeczna, gospodarcza, oświatowa i kulturalna*, I. Schiper, A. Tartakower, A. Haftka (ed.), vol. I, Publ. Żydzi w Polsce Odrodzonej, Warszawa 193.

[2] Łuszczkiewicz W., *Sprawozdanie z wycieczki naukowej odbytej w lecie 1891 roku,* [in:] *Sprawozdanie Komisyi do badania Historyi Sztuki w Polsce*, vol. II, Publ. AU Kraków, Kraków 1896, 173–177.

[3] Grotte A., *Deutsche, böhmische und polnische Synagogen typen vom XI. bis Anfang des XIX. Jahrhunderts*, Publ. Der Zirkel, Berlin 1915.

[4] Pęckowski J., *Dzieje miasta Rzeszowa do końca XVIII w.,* Publ. Ruthenus, 2002, 122, 125, 167 and 211.

[5] Krautheimer R., *Mittelalterliche Synagogen*, Publ. Frankfurter Verlags-Anst, Berlin 1927.

[6] Szyszko-Bohusz A., *Materiały do architektury bóżnic w Polsce*, Praca Komisji Historii Sztuki, vol. IV, Publ. PAU, Warszawa–Kraków–Łódź–Lublin–Poznań–Wilno 927.

[7] Bałaban M., *Bóżnice obronne na wschodnich kresach Rzeczypospolitej,* [in:] *Studia historyczne*, M. Bałaban, Publ. Księgarnia M.J. Freid i S-ka, Warszawa 1927, 93–99.

[8] Bałaban M., *Zabytki historyczne Żydów w Polsce,* Publ. Towarzystwo Krzewienia Nauk Judaistycznych w Polsce, Warszawa 1929.

[9] *Żydzi w Polsce Odrodzonej: działalność społeczna, gospodarcza, oświatowa i kulturalna,* I. Schiper, A. Tartakower, A. Hafftka (ed.), Publ. Żydzi w Polsce Odrodzonej, Warszawa 1932.

[10] Zajczyk Sz., *Architektura barokowych bóżnic murowanych w Polsce,* [in:] *Biuletyn Historii Sztuki i Kultury,* Publ. Zakład Architektury Polskiej i Historji Sztuki Politechniki Warszawskiej, vol.1. no 4, 1932/1933, 186–195.

[11] Piechotkowie M.K., *Bóżnice drewniane,* Publ. Budownictwo i Architektura, Warszawa 1957.

[12] Piechotkowie M.K., *Bramy Nieba. Bóżnice drewniane na ziemiach dawnej Rzeczypospolitej,* Warszawa 1997.

[13] Burchard P., *Pamiątki i zabytki kultury żydowskiej w Polsce,* Publ. Burchard Edition, Warszawa 1990.

[14] Piechotkowie M.K., *Bramy Nieba. Bóżnice murowane na ziemiach dawnej Rzeczypospolitej,* Publ. Krupski i S-ka, Warszawa 1999.

[15] Urban K., *Cmentarze żydowski, synagogi i domy modlitwy w Polsce w latach 1944–1966 (wybór materiałów)*, Publ. Nomos, Kraków 2006.
[16] Potocki A., *Żydzi w Podkarpackiem*, Publ. Libra, Rzeszów 2004.
[17] Potocki A., *Bieszczadzkie judaica, od Sanoka po Sianki*, Publ. Carpathia, Rzeszów 2017.
[18] Potocki A., *Żydzi rymanowscy*, Publ. Libra, Rzeszów 2018.
[19] Kotula F., *Tamten Rzeszów, czyli wędrówka po zakątkach i historii miasta*, Publ. Zimowit, Rzeszów 1997.
[20] Hennig W., *Rzeszowski alfabet*, Publ. Podkarpacki Instytut Książki i Marketingu, Rzeszów 2012.
[21] GUS, Tabele demograficzne, 30.06.2014, https://stat.gov.pl.
[22] Rapacki W., *Ludność Galicji*, Publ. by Author, Lwów 1874, 53.
[23] Dylewski A., Olej-Kotbus A., Kotbus K., *Judaica*, Publ. CARTA BLANCA, Warszawa 2010, 18.
[24] Kotula F., *Obwarowania Rzeszowa i rozwój przestrzenny miasta w XVII–XVIII wieku*, [in:] Pięć *wieków miasta Rzeszowa XIV–XVIII*, F. Błoński (ed.), Publ. PWN, Warszawa 1958, 185.
[25] Przyboś A., *Rzeszów na przełomie XVI i XVII wieku*, [in:] *Pięć wieków miasta Rzeszowa XIV–XVIII*, F. Błoński (ed.), Publ. PWN, Warszawa 1958, 63–158.
[26] Wilczyk W., *Niewinne oko nie istnieje*, Publ. by Galeria Atlas Sztuki and Ha!art, Łódź–Kraków 2009, 128.

If you want to quote this article, its proper bibliographic entry is as follow: Kuśnierz-Krupa D., Tobiasz L., *Synagogues in Podkarpacie – Prolegomenon to research*, Technical Transactions, Vol. 9/2019, pp. 17–32.

TECHNICAL TRANSACTIONS 9/2019
ARCHITECTURE AND URBAN PLANNING
DOI: 10.4467/2353737XCT.19.093.10875
SUBMISSION OF THE FINAL VERSION: 30/07/2019

Michał Krupa orcid.org/0000-0003-0093-2249
michal.krupa@pk.edu.pl
Institute of Urban Design, Faculty of Architecture, Cracow University of Technology

Mateusz Budziakowski orcid.org/0000-0002-6258-7244
Doctoral Studies, Faculty of Architecture, Cracow University of Technology

Lipnica Murowana – historic heritage and its conservation protection

Lipnica Murowana – zasób zabytkowy i jego ochrona konserwatorska

Abstract

The article presents the cultural heritage of the mediaeval town of Lipnica Murowana, located in Lesser Poland in Bochnia County. This historic town can boast valuable architectonic and urban design buildings. These are the church of St. Leonard; the church of St. Andrew the Apostle; the church of St. Simon; the Starost's House; the Ledóchowski Manor; the school building, relics of town housing and, primarily, the mediaeval urban layout with a market square. The article presents the history of the abovementioned historic buildings and spaces, and analyses their current protection and conservation guidelines.

Keywords: Lipnica Murowana, historic heritage, architectonic monuments in Lipnica Murowana, urban design monuments in Lipnica Murowana, conservation protection

Streszczenie

Artykuł dotyczy dziedzictwa kulturowego niegdysiejszego średniowiecznego miasta Lipnicy Murowanej, położonego w Małopolsce, w powiecie bocheńskim. Ten zabytkowy ośrodek ma na swoim terenie cenne zabytki architektury i urbanistyki. Są to: kościół pw. św. Leonarda; kościół pw. św. Andrzeja Apostoła; kościół pw. św. Szymona; Dom starościński; Dwór Ledóchowskich; budynek szkoły, relikty małomiasteczkowej zabudowy mieszkalnej, a przede wszystkim zachowany średniowieczny układ urbanistyczny z rynkiem. W artykule dokonano analizy historii wymienionych obiektów i przestrzeni zabytkowych wraz z przeglądem ich bieżącej ochrony oraz wytycznymi konserwatorskimi.

Słowa kluczowe: Lipnica Murowana, zasób zabytkowy, zabytki architektury Lipnicy Murowanej, zabytki urbanistyki Lipnicy Murowanej, ochrona konserwatorska

1. Introduction

Lipnica Murowana, a small settlement located in Bochnia county, approximately 50 km from Krakow, is an example of a well-preserved mediaeval chartered town layout, developed in 1326 [1]. For centuries, the former town used to be a significant centre in the region. It was affected by both numerous town-forming factors (such as its location along trade routes, privileges, influx of settlers) and those hindering that development (great fires, wars, floods). Despite its turbulent history, the town, currently degraded to the rank of a village commune, has basically retained its shape and can serve as excellent material for historical, urban and architectonic research.

Besides the orthogonal town layout, Lipnica can boast a relatively large number of historic buildings. They include both monuments of urban design in the form of a mediaeval market square, and of architecture like the church of St. Leonard listed in the UNESCO World Heritage List; the church of St. Andrew the Apostle; the church of St. Simon; the Starost's House; the Ledóchowski Manor; the school building and relics of small-town housing [2].

The goal of this article is to describe the state of the heritage buildings in Lipnica Murowana, determine the forms of their current protection and outline the conservation requirements in this respect.

2. Urban design heritage

The historic urban layout of Lipnica Murowana, which has been very well preserved since the mediaeval period, is of great importance in terms of the voivodeship. The layout is a defined, orthogonal urban structure with a market square, streets running from its corners, inscribed within the oval of the town walls [3, 4]. The houses around the market square are single-family houses, farmhouses and utility buildings, sometimes adapted for trade and service functions. The houses are mostly one-storey buildings with an attic, and multi-storey. A few buildings from the 19th and the beginning of the 20th century have survived till today, but buildings from the inter-war and post-war periods are predominant. The majority of buildings are traditional structures typical for the town, though there are some rescaled buildings with modern details which clash with the historic cultural landscape.

The mediaeval urban layout of Lipnica Murowana is under statutory conservation protection as it was listed in the voivodeship monument register (no A-82) in 1976 [2].

In the authors' opinion, the urban layout of Lipnica with its picturesque market square requires special and well thought-out conservation protection. The market square should undergo complete restoration; ahistorical elements such as the fountain should be removed; the division into plots, the form and dimensions of buildings should be preserved whenever possible. It is also worth considering the possibility of creating a catalogue of building patterns – materials, colours, details – to be used by owners of properties located within the protected zone.

Fig. 1. Bird's-eye view of the mediaeval urban layout of Lipnica Murowana nowadays (photo by W. Gorgolewski)

3. Architectural monuments

Certainly the most valuable building in Lipnica is the cemetery church of St. Leonard, dating back to the 15th century. It is one of the most valuable wooden churches in Lesser Poland [5], owing to which in 2003 it was entered in the UNESCO World Cultural and Natural Heritage List.

The church is well preserved. Recently its grounds have been tidied, the surrounding fence has been modernised, cemetery paths have been paved and a parking lot has been built. Inside the church there is the alleged "Światowid column". According to local tradition, the church was erected on the site of another one built in 1141, which in turn had replaced a pagan temple of which the "column" was a part. However, radiocarbon dating carried out by Prof. Natalia Piotrowska from the Institute of Physics, Silesian University of Technology, on the initiative of M. Budziakowski, ruled out the pre-Christian origins of the column, dating the time of tree felling to the turn of the 15th and 16th centuries (which corresponds to the assumed time when the actual church was built). The church interior is decorated with paintings from various periods, from the end of the 15th till the beginning of the 18th century. The presbytery is decorated with polychromes depicting the Crucifixion, the Last Supper and the Final Judgement; and the nave – scenes from the Passion and the Decalogue [6, 7].

Naturally, the church is listed in the voivodeship register of immovable monuments, where it was inscribed in 1969, under no A-154.

Writing about conservation guidelines, one has to emphasise the church surroundings where the traditional forms of tombstones ought to be used, ruling out light materials such as pink marble, or not refined enough like terrazzo. Particular care should be taken of characteristic, heavy sandstone slabs, on which inscriptions and ornaments are gradually effaced by weather conditions.

Fig. 2. View of the church of St. Leonard in Lipnica Murowana nowadays (photo by authors)

In the context of protecting the cultural landscape in Lipnica, another valuable building is the parish church of St. Andrew the Apostle. It was founded by King Kazimierz Wielki (Casimir the Great) in 1363 [8]. The church has one nave, a narrowed presbytery, and a tower on massive buttresses which dominates Lipnica. Six altars, a Gothic sculpture of Our Lady with Child from the 14th century, a 17th-century figure of Crucified Christ and two mediaeval baptismal fonts are of considerable cultural value. The church is in good physical condition. A decade ago the roofing of the tower was replaced and the vertical insulation of foundations was made.

The church is listed in the voivodeship register of immovable monuments, where it was inscribed in 1969, under no A-155.

As far as conservation guidelines are concerned, it is necessary to revitalise the church surroundings by restoring the outside stairs.

Fig. 3. View of the parish church of St. Andrew the Apostle in Lipnica Murowana nowadays (photo by authors)

There is one more historic church building in Lipnica Murowana. This is the Baroque church of St. Simon. The building was founded by Stanisław Lubomirski, the Starost of Lipnica, in 1648. The church might have been erected on the site of the family home of St. Simon of Lipnica as a votive church. The building has one nave and a gable roof with a little bell turret. At the entrance, there is a bell-gable, and in the vicinity there stands the statue of King Władysław Łokietek, the founder of Lipnica [9, 10].

The state of preservation of the church can be described as very good. The church furnishings – the altar and pews – were renovated during the last decade.

The church is under statutory conservation protection and was entered on the voivodeship register of immovable monuments in the year 1969, under no A-156.

Because of the very good condition of the church it does not require conservation treatment at present.

Fig. 4. View of the church of St. Simon in Lipnica Murowana nowadays (photo by authors)

Besides church objects, there are also valuable monuments of lay architecture in Lipnica Murowana. Among these, one should mention the Starost's House, also known as the Starost's Manor. It was erected after the "Swedish deluge", probably at the turn of the 18th century, from stones obtained from the dismantled town walls. It is a massive, masonry building with arcades. It must have served an administrative function, and was probably the seat of the town steward [...].

The building is entered in the voivodeship register of immovable monuments, where it was inscribed in 1978, under no A-148.

Despite statutory conservation protection, for ten years the object has been under renovation which has not been completed yet. During this period, a new tiled roof covering was made with ahistorical, disproportionate dormers. It is worth mentioning that the analysed object requires a new inventory and current valuation. A possible renovation or conversion should be related to adapting the building to a new function, using traditional forms and local materials.

While discussing the cultural heritage of Lipnica, one cannot ignore the Ledóchowski family manor. This is a manor built in the French style, neo-classicist, recalling the Baroque urban layout in which the composition axis led from the main square to the manor and the manorial garden. The manor was erected at the beginning of the 18th century by Kazimierz Janota-Bzowski, the first owner of Lipnica after the partitions. It is a multi-storey building, with partial basement, and an attic. The interior has an axial layout with 5 chambers (front and 4 on the sides) on the ground floor, and one upstairs.

Fig. 5. View of the Starost's manor in Lipnica Murowana nowadays (photo by authors)

The Ledóchowski Manor is listed in the voivodeship register of immovable monuments, where it was inscribed in 1976, under no A-82.

At present, despite its satisfactory physical condition, the building remains unused, which is a pity because it might house a local museum, a cultural centre or a gallery. In order to do that, besides adapting the structure to a new function, the roof truss and covering would have to be replaced.

Fig. 6. View of the Ledóchowski Manor in Lipnica Murowana nowadays (photo by authors)

Fig. 7. View of the former school building in Lipnica Murowana nowadays (photo by authors)

Another valuable object in Lipnica Murowana is the former school building. It is a one--storey, masonry building. Originally, it housed the town elementary school, and since the second half of the 20th century a regional chamber functioned there, which is closed at present. The former school building is located in the direct vicinity of the parish church.

In 2010, the former school building was entered in the voivodeship register of immovable monuments under no A-1190/M.

Its state of preservation is good, yet requires restoration which should include roof repairs and adapting the building to its new function, related, for instance, to tourist services.

Besides the already mentioned well-known historic structures located in Lipnica Murowana, valuable relics of former housing can also be found in this former town. They are one-storey houses from the turn of the 20th century, typical for small, historic towns [10]. Unfortunately, most of them are in poor condition and are gradually falling into disrepair. They certainly require better conservation protection and restoration, as well as listing in the county heritage register. The latter remark refers primarily to the houses surrounding the market square, and those located within the mediaeval urban layout (no: 106, 142, 34, 113, 108, 145, 132, 76 and 134). It is also suggested that selected utility buildings reflecting the agricultural character of the village be protected as well [11].

Fig. 8. View of the historic houses near market square in Lipnica Murowana nowadays (photo by authors)

4. Summary

To conclude these initial considerations on the historic heritage of Lipnica Murowana and its protection and restoration, it has to be said that basically this heritage is well preserved. It consists of monuments of urban design and architecture, which are mostly under statutory conservation protection as they are listed among the immovable monuments of the Lesser Poland Voivodeship. In Lipnica, there is a valid local spatial development plan (LSDP), which reinforces protection with its regulations concerning the protection of the cultural landscape. It is worth noting here that a protection zone for the cultural heritage and modern cultural monuments was created in the LSDP, within which there are a zone of strict conservation protection of historic objects and areas, a zone of partial conservation protection of historic objects and areas, a zone of historic landscape objects and areas, and a zone of cultural documentation. In these zones it is imperative to preserve the existing architectural and urban planning values of a town, to individually protect objects and complexes inscribed in the register and on the monument list including their landscape, natural, viewing and functional conditions within the viewing areas, valuable buildings and historic complexes, and to maintain historical interrelations in the territorial context. In the context of heritage protection, the LSDP assumes that all planning and investment activities will be subordinated to protecting the cultural heritage [12].

An important and valuable initiative is the idea of creating a cultural park in the centre of Lipnica Murowana, which is another statutory form of heritage protection. The park would encompass the centre of the village with the church of St. Leonard, the churchyard and the Ledóchowski Manor.

In the context of these considerations, one should also emphasise the urgent need to preserve the surviving section of the town wall, which is in very poor condition and is not under any form of protection [13]. The structure should be secured as soon as possible, and then should be restored and put under statutory protection.

To sum up, it can be claimed that the cultural landscape of Lipnica Murowana is of special significance for our national culture. It includes both the material value related to the above described heritage, and immaterial values in the form of the tradition of the place and local customs. These features make it one of more unique mediaeval towns in Lesser Poland, which requires particular protection and care. That protection should be carried out with the support of heritage protection services, statutory forms of protection, local government and local communities.

References

[1] *Lipnica Murowana. Gród króla Władysława Łokietka*, J. Smołuch (ed.), Publ. Akademickie Press, Kraków 2007.

[2] *Rejestr zabytków nieruchomych woj. małopolskiego*, https://www.wuoz.malopolska.pl (access: 01.07.2019).

[3] Krasnowolski B., *Lokacyjne układy urbanistyczne na obszarze ziemi krakowskiej w XIII i XIV w.*, part II, Publ. WNAP, Kraków 2004, 119–124.
[4] Berdecka A., *Lokacje i zagospodarowanie miast królewskich w Małopolsce za Kazimierza Wielkiego (1333–1370)*, Publ. Zakład Narodowy im. Ossolińskich, Wrocław 1982, 45, 59, 108.
[5] Kornecki M., *Kościoły drewniane w Małopolsce*, Publ. ODZ, Warszawa–Kraków 1999, 69–70.
[6] Kydryńska A., *Kościółek św. Leonarda w Lipnicy Murowanej*, Wiadomości Konserwatorskie – Journal of Heritage Conservation 5/1958.
[7] Brykowski R., *Drewniana architektura kościelna w Małopolsce XV wieku*, Publ. Zakład Narodowy im. Ossolińskich, Wrocław 1981, 71, 73, 75, 81, 100, 102, 105.
[8] Brykowski R., *Lipnica Murowana,* [in:] *Architektura gotycka w Polsce*, T. Mroczko, M. Arszyński (ed.), vol. 2, Warszawa 1995.
[9] Kornecki M., *Kościoły Lipnicy Murowanej*, Currenda, 10–11/1992.
[10] Dutkiewicz J.E., *Katalog Zabytków Sztuki w Polsce*, vol. 1, *Woj. krakowskie. Powiat bocheński*, Publ. Ministerstwo Kultury i Sztuki, Warszawa 1951, 8.
[11] Budziakowski M, *Lipnicki słup podcieniowy – identyfikacja przestrzeni miejskiej*, Wiadomości Konserwatorskie – Journal of Heritage Conservation 54/2018, 67–73.
[12] *Miejscowy plan zagospodarowania przestrzennego – Lipnica Murowana*, http://www.lipnicamurowana.pl/plan-przestrzenny-gminy.html (access: 02.07.2019).
[13] Niewalda W., *Badania nad murami miejskimi w Lipnicy Murowanej*, Teka Komisji Urbanistyki i Architektury 3/1969, 145–158.

If you want to quote this article, its proper bibliographic entry is as follow: Krupa M., Budziakowski M., *Lipnica Murowana – historic heritage and its conservation protection*, Technical Transactions, Vol. 9/2019, pp. 33–44.

TECHNICAL TRANSACTIONS 9/2019
ARCHITECTURE AND URBAN PLANNING

DOI: 10.4467/2353737XCT.19.094.10876
SUBMISSION OF THE FINAL VERSION: 7/08/2019

Mariusz Twardowski orcid.org/0000-0001-5177-395X
mariusz.twardowski@pk.edu.pl
Institute of Urban Design of Faculty of Architecture, Cracow University of Technology

Agnieszka Żabicka orcid.org/0000-0001-8835-4564
zabicka.agnieszka@gmail.com
Faculty of Architecture, Cracow University of Technology

Andrés Ros Campos
Spain. roscampos@uchceu.es
Department of Projects, Theory and Technique of Design and Architecture, Cardenal Herrera University-CEU, CEU Universities, Valencia

Houses and skyscrapers of Manhattan – a horizontal or vertical city?

Domy i wieże Manhattanu – miasto horyzontalne czy wertykalne?

Abstract

Residential towers undeniably changed the reality that surrounds us. Vertical structures have influenced the landscape of cities by shaping new, previously unknown panoramas. Infinite peripheries were split and reassembled again in the vertical form. Is it possible to create a comfortable living space in a small area? Can residential towers fit into a fully fledged and well-functioning urban structure? Problematic aspects of this scenario are discussed on the basis of the most representative example in the world, which is Manhattan, located in New York City. Analysis of the urban structure of specific districts and examples of residential towers enables the presentation of the differences, advantages and disadvantages resulting from a specific given forms of architecture and urban planning.

Keywords: New York, Manhattan, city, house, residential tower, hybrid

Streszczenie

Wieże mieszkalne niezaprzeczalnie zmieniły otaczającą nas rzeczywistość. Wertykalne struktury wpłynęły na krajobraz miast, kształtując nową, nieznaną wcześniej panoramę. Nieskończone peryferia zostały poddane rozczłonkowaniu funkcjonalnemu i ponownie scalone w formie pionowych konstrukcji. Czy dzięki temu udało się stworzyć dogodną przestrzeń życia na niewielkim terenie? Czy wieże mieszkalne mogą wpisać się w pełnowartościową i dobrze funkcjonującą strukturę miejską? Problematykę omówiono na podstawie najbardziej reprezentatywnego w świecie przykładu, jakim jest nowojorski Manhattan. Analiza struktury urbanistycznej poszczególnych dzielnic wyspy oraz konkretnych przykładów wież mieszkalnych pozwoli na dokładne przedstawienie różnic, zalet i wad wynikających z danej formy architektury i urbanistyki.

Słowa kluczowe: Nowy Jork, Manhattan, miasto, dom, wieża mieszkalna, hybryda

1. Introduction

Residential towers have been built since prehistoric times. The first examples that can be found primarily in the territories of France, Great Britain and Italian cities such as San Gimignano, Bologna, had various characters. They were residential buildings, also providing a shelter in uncertain times[1]. Over the years, along with urban development and technological progress, architecture and urban planning have gone through numerous changes and has been presented with new opportunities. The horizontal landscape began to give way to vertical forms, which irretrievably changed the panorama of big cities. It would seem that the present world would not function without the skyscrapers that concentrate city life, but they played the largest role at the end of the 19^{th} century. The invaluable influence of the Industrial Revolution and the Chicago School have made the city rise upwards[2]. Skyscrapers have become the answer to the problem of the rapid spread of people to suburban areas (urban sprawl). They allow the population to be concentrated in a limited area. They become an inspiration for future creativity and reflection, and a change in style and quality of life.

The city consists of elements necessary for its proper functioning. The urban structure consists not only of single residential buildings but also public buildings, cultural facilities, recreational spaces, and technical and transport structures. Street grids mark building plots, squares and parks.

In front of our eyes, the concept of the city is changing. From fragmented structure extended on the endless peripheries, it is concentrated into the compact form of the tower. There are not only houses and recreational spaces for residents, but also offices, shops, kindergartens, schools, hospitals, restaurants, cinemas and theatres. Functionally self-sufficient units create vertical cities within the city. Is it worth considering whether hybrid towers are able to replace metropolises? What differences, advantages and disadvantages do they have? Will their appearance in the city improve the quality of life and create a connection between the people and the place? Can concrete jungles compete with historical districts of Manhattan?

2. Manhattan

New York is a global capital of life, economy and culture. It attracts both people and business. The former capital of the country is an amazing, diverse and mysterious city. Located on the east coast of the United States, it seems to be created from many myths and tales, it is the symbol of America, the dream destination. In its heart is Manhattan,

---

[1] The first knight towers, built in the 10^{th} century, come from the cities of Norman and Anjou. Later they were seen in Great Britain, where they func-tioned mainly for defence. The main reason and motivation for building towers in the medieval cities of Italy was primarily the lack of space for the spread of urban structures. Cities often built in the hills were built with countless towers that are still part of the Tuscan landscape [9, pp. 20–21].

[2] The Chicago School was founded in the United States at the end of the 19^{th} century. Its greatest achievement was the introduction of a steel struc-ture that allowed movement from horizontal architecture of limited storeys to vertical towers [10].

surrounded by the Hudson River and the East River. The picturesque island with its limited area for development means that construction cannot spread infinitely beyond its shoreline. These limitations, however, stimulate the creativity and imagination of world-famous urban planners and architects. It is thanks to them that Manhattan has a carefully planned city grid and the largest number of squares and parks that we can find in any American city, including the most famous – Central Park.

Fig. 1. Panorama of Manhattan as seen from Ellis Island (photo by Agnieszka Żabicka)

The relationships between the architecture and the surrounding landscape, and the unusual number of skyscrapers create the unforgettable panorama of Manhattan[3]. The unprecedented population density and the limited area of the island create a constant drive for taller more beautiful buildings.

3. Historical districts

New York is undeniably a city of contrasts, which are apparent not only in the diverse community but also in urban planning, architecture and details. Despite the overall image of Manhattan and its most famous panoramic views of the financial district reaching into the clouds in the south and Midtown rising to the sky just next to Central Park, this island is not just a high-rise forest. There are historical districts such as Little Italy, SoHo, West Village,

[3] The number of skyscrapers rising above 150 meters in New York by the end of 2018 was calculated at 272, and by the end of 2019, this number is going to increase by 33 [22].

Greenwich Village, East Village and Harlem. Buildings there as opposed to skyscrapers centres are low having several floors. Often, there are historical objects of inestimable value and the streets in this urban structure are vibrant with life. The pavements and cycle paths throng with residents. The buildings of the human scale preserve the harmony of man in connection with the environment and place and foster a sense of safety.

Fig. 2. Life on the streets of Little Italy (photo by Agnieszka Żabicka)

Little Italy is now more of a tourist attraction than a district that is actually inhabited by people of Italian origin[4]. Many restaurants, small shops and bars evoke the atmosphere of a European city. Relatively wide streets with small buildings allow people to ‘catch the breath’. Multi-coloured buildings increase the attractiveness and individuality of the place. There are also some of the best bars in New York in this district. The inhabitants’ identity is created not only with the building itself, but also with the district that provides residents with the necessary facilities for daily life.

Another example of the Manhattan neighbourhood is Greenwich Village. Its centre with Washington Square Park has become a popular place to visit for students, tourists and residents. It is an extraordinary part of the city in which “modernity neighbours with history” [5]. Narrow streets, which are lacking in other parts of Manhattan, have numerous trees and cobbled streets creating a rural picture that almost does not match the rest of the island. People can find single-family houses, yards, squares and parks here.

[4] Little Italy was named after a large group of immigrants mainly from Naples and Sicily who settled in this area at the end of the 19th century [24].

Is it possible to transfer this extraordinary character of small, historical, artistic districts to the concrete jungle, the maze of towers? Is the energy of the city, the sense of security and easy accessibility possible to obtain in skyscrapers?

Fig. 3. Small houses of Lower Manhattan which are rich in greenery (photo by Agnieszka Żabicka)

4. Residential hybrids

Urban hybrids provide answers to the questions posed at the end of the previous section. Multifunctional facilities, which apart from apartments and offices, have complementary functions and maintain the continuity of the 'life' of the building during the day and after sunset. These are skyscrapers in which there are no dead spaces, and the most-needed elements of the extensive urban structure are at residents' fingertips. Towers offer a different perception of their surrounding areas and they have a significant influence over the identity of the districts they occupy.

5. Beekman tower (Eight Spruce), proj. Frank Gehry, 2011

One of the unique buildings in New York is the Eight Spruce residential tower. This is a project by Frank Gehry that was completed in 2011 and cuts into the urban plan of Lower Manhattan. This is the first skyscraper of a world-renowned architect. Although it has been already eight years since it was completed, it remains the tallest luxury residential tower in this part of the city. The main facade of the skyscraper faces the central part of the island and the East River. Because of the wide arteries of the Brooklyn Bridge and the low buildings of Lower Manhattan, there is little to obscure its view. The only simple, geometric facade is directed at the Downtown Manhattan financial centre. The building rises to 271.6 m. This seventy-six-storey tower, covered with stainless steel, is a symbol of wealth. The skin reflects the rays of the rising and setting sun. It shows a fluid breakthrough between modern architecture and the futuristic age of digitalisation [20]. The sculptural form of the main facade almost is symbolic of the waves of the East River, creating their contemporary interpretation. The building, designed around the main shaft of fifteen elevators, houses more than nine hundred apartments, and its underground section can accommodate 175 cars.

Beekman Tower is an excellent example of urban hybrids. It combines not only high--class apartments and accompanying facilities. There is also a hotel, and the six-story building base includes a kindergarten, a primary school and a floor dedicated to the administration of the New York Downtown Hospital. The building also houses an amphitheatre, cinema, a playground, a library and a spa and wellness section for residents. Various facilities create a compact structure. Each of the main facilities has a separate entrance; in this way, the architect was able to preserve the privacy of residents. The accessibility to basic services makes it unnecessary for residents to leave the building. The Eight Spruce project also has a positive effect on the safety of residents and makes their lives easier. Children can move between home and kindergarten, or school, almost without leaving the tower, without going through any street. It has become an incentive for many tenants and makes the building unique.

Fig. 4. Beekman Tower (photo by Agnieszka Żabicka)

6. 432 Park Avenue, proj. Rafael Viñoly, 2015

The crowded Midtown in the middle of Manhattan does not seem to be able to accept new buildings anymore. Although the density of buildings is still growing, the goal is to design a building higher than the others, with the smallest build area. With reference to the skyscraper at 432 Park Avenue, it has been said that "the Avenue beats all the records so far – it will be the slimmest, highest and definitely the most expensive" [14]. This residential tower was completed in 2015. The skyscraper at 432 Park Avenue stands out over the surrounding buildings and trees of Central Park. The tower was designed by the office of Uruguayan architect Rafael Viñoly, with unparalleled slenderness at these heights and concrete construction. The geometric shape of the cuboid has a height-to-width ratio of 15:1. The white, monolithic form, which is more than four hundred and twenty-five meters high, is the second highest building in New York after One World Trade Center. Eighty-five floors house one hundred and four apartments serviced by ten elevators [18]. By placing residences over sixty-three meters high, the property offers an unobstructed view of Manhattan's green lungs – Central Park.

Fig. 5. 432 Park Avenue (photo by Agnieszka Żabicka)

The modern aesthetics of the facade with respect for traditions, seems to reflect the orthogonal grid of Manhattan streets. Clean lines and scaled windows, allowing for the best lightning and views, create an elegant, symmetrical form, and give the block a lightness.

432 Park Avenue in addition to luxury apartments also offers offices, conference spaces, a restaurant overlooking one of Manhattan's main streets (57th Street), golf fields, a health and relaxation zone, a swimming pool, a fitness club and underground parking.

7. VIΛ 57 west, proj. Big, 2016

An excellent answer to the question of how to enclose a piece of tradition in a modern form is the project of the Danish architectural studio BIG. Finished in 2016, this hybrid building is a combination of a European building quarter with a courtyard in the middle and a high-rise that is characteristic of this part of New York. It is 142 meters high in one of the corners and proudly pierces Manhattan's air as a compositional dominant feature on the shoreline, open to the Hudson River.

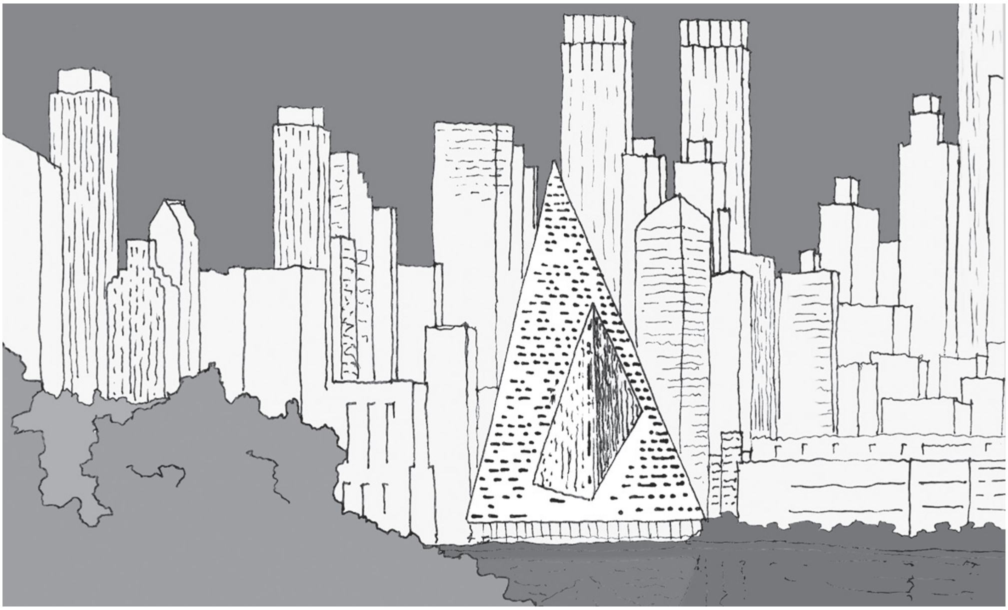


Fig. 6. VIΛ tower with the view of Manhattan (by Agnieszka Żabicka)

The other three corners remain at the level of the bottom glazed base. The use of a hyperbolic paraboloid as an idea for the main form of the building has provided each apartment with a direct view of the river and the Jersey City skyline, and additionally, allows natural light to penetrate both the interior of 709 apartments and the inner courtyard. The garden of the inner courtyard is connected to the lobby of the residential tower. It has become the green heart of the building, which gives a sense of privacy and security. It is isolated from the busy streets, but at the same time, it does not cut off residents from the rest of the outside world. The innovative approach to the project means that the user does not have the impression that the courtyard becomes a vertical tunnel surrounded by high walls, the feeling of life inside a well (which is characteristic of the concrete forest of skyscrapers) is completely rejected here.

The scaled VIΛ sculpture proudly faces the Manhattan skyline that is visible from the Jersey City shore. In addition to the predominant housing function, there are also many amenities. The building has relaxation areas, space for organising various types of parties and cultural events, a golf simulator, a cinema room, a swimming pool, a tennis court, an exercise room, and a room for playing poker [11]. All public or semi-private functions have been placed in a glazed base, thus obtaining separation from the private part.

8. 56 Leonard, proj. Herzog & De Meuron, 2017

The most recent of the presented examples is the project of the world-renowned Swiss architectural office Herzog & de Meuron. Completed in 2017, the residential tower reaches a height of 250 m, housing fifty-seven functional floors and 146 high-class apartments [19]. The use of raw concrete and cantilevered cubes, as well as cooperation with artists creates a place where architecture blends with art, and residents can enjoy unlimited life in the clouds.

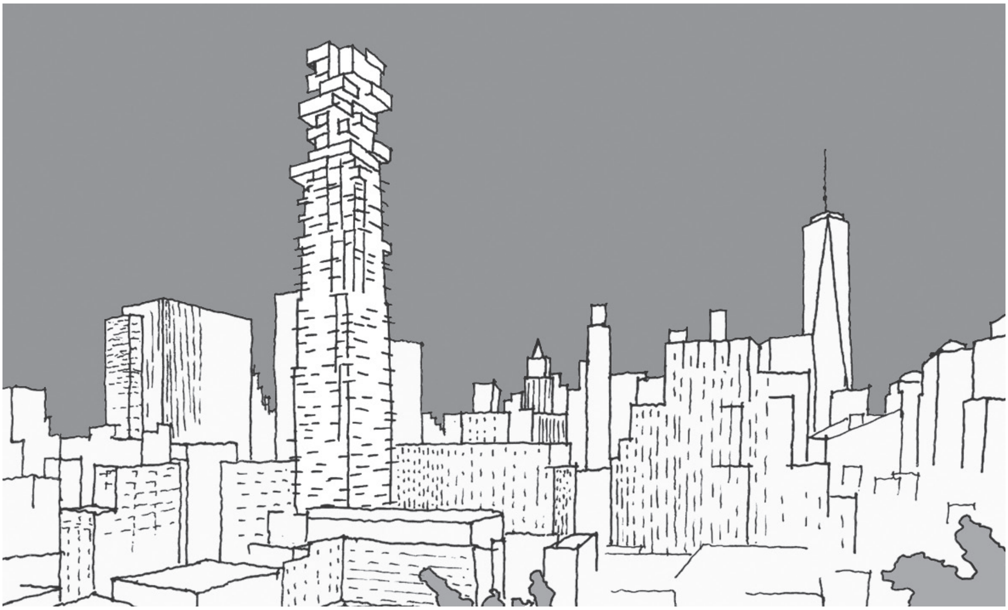


Fig. 7. 56 Leonard (by Agnieszka Żabicka)

A personalised tower, resembling glass houses placed on top of each other, creates a friendly environment. Architects departed from the idea of creating a homogeneous solid, whilst simultaneously giving the tower an individual character. Each floor plan is different, they differ with regard to cantilever bay windows, and the shape and arrangement of balconies. At the same time, the seemingly massive and vibrating shape smoothly transforms into a sky--like background thanks to materials that reflect the surroundings.

In addition to the apartments, the tower has other facilities such as a theatre, cinema, conference centre, a twenty-three-metre swimming pool, a fitness club, a library and playgrounds for children. Residents can therefore spend entire days without actually leaving the building.

9. Summary

New York is a city of contrasts, and at the same time, an urban 'heart of the world' [7]. On the one hand, there are vertical skyscrapers towering above the clouds, on the other, there are low, atmospheric, historical districts with greenery, designed with respect for human scale. These are two completely different systems of structures, and yet their coexistence maintains the balance of Manhattan.

Fig. 8. Manhattan as viewed from Central Park (photo by Agnieszka Żabicka)

For years, architects have made every effort to ensure that the surrounding urban tissue supports and enhances the quality of our lives. Hybrid towers are one of the solutions aimed aimed at, at least partial, replacement the urban unit, to at least a partial extent. Within a small area, we can find the most important elements necessary for everyday life such as shops, recreation areas, and spaces for work and relaxation, which in a horizontal city, are spread over a large area. As a result of this, the time devoted to the everyday transfer to work or school in ubiquitous traffic jams is shortened. People can be at the centre of cultural events. Distances to theatres, opera houses, shops and offices have been minimised. The applied solutions support pro-ecological activities and a healthy lifestyle. All necessary elements and functions are on the doorstep.

But can concrete forests compete with the climatic and historical districts that can be found, for example, in Lower Manhattan? Does the constant emphasis on the sense of privacy mean that people isolate themselves? The answer is a matter of opinion and there are both opponents and supporters of each vision. Individual zones have their own unique atmosphere and everyone can find their own identity.

Apparently, it can be concluded that horizontal structures, which are closer to the ground, are at the same time closer to nature, greenery and a scale adapted to human beings. In such tissue, people can more easily and more naturally create semi-private zones in the form of courtyards. Horizontal cities need more space and this is not infinite. In dense cities, it is easier to design vertical tissue. It allows giving up cars and public transport, and districts do not form commuter towns. All public, cultural, and sports facilities are located within walking range and the space live continuously. It is unnecessary to resign from horizontal tissue, but in cities with high density, the advantage of vertical forms is undeniable.

References

[1] a+t research group, *This is hybrid. An analysis of mixed-use buildings,* a+t architecture publishers, Vitoria-Gasteiz 2014.
[2] Condit C., *The Chicago School of Architecture,* University of Chicago Press, Chicago 1952.
[3] Gyurkovich M., *Hybrydowe przestrzenie kultury we współczesnym mieście europejski,* Wydawnictwo PK, Kraków 2013.
[4] Jopek D., *Czynniki kształtujące przestrzenną formę miasta,* [in:] *Rozwój Regionalny i Polityka Regionalna 42,* Poznań 2018.
[5] Kantarek A., *O orientacji w przestrzeni miasta,* Wydawnictwo PK, Kraków 2013.
[6] Koolhaas R., *Deliryczny Nowy York,* Wydawnictwo Karakter, Kraków 2013.
[7] Kosiński W., *„Serce* świata*" – Manhattan,* Czasopismo Techniczne, 3-A/2008, 99–109.
[8] Paprzyca K., *Attractiveness of the Manhattan District,* Czasopismo Techniczne, 3-A/2015, 143–59.
[9] Twardowski M., *Wieże mieszkalne,* Wydawnictwo PK, Kraków 2017.
[10] www.arch2o.com/chicago-school-architecture-skyscrapers (access: 30.01.2019).
[11] www.archdaily.com/794950/via-57-west-big (access: 31.01.2019).
[12] www.archdaily.com/870107/305-56-leonard-street-herzog-and-de-meuron (access: 31.01.2019).
[13] www.newyorkbygehry.com (access: 30.01.2019).
[14] www.nowawarszawa.pl/432-park-avenue-najwyzszy-budynek-mieszkalny-w-nowym-yorku/ (access: 30.01.2019).
[15] www.nypap.org/preservation-history/soho-cast-iron-historic-district/ (access: 30.01.2019).
[16] www.nytimes.com/2011/02/10/arts/design/10beekman.html (access: 30.01.2019).
[17] www.nytimes.com/2018/02/19/nyregion/little-italy-manhattan-fire.html (access: 30.01.2019).
[18] www.skyscrapercenter.com/building/432-park-avenue/13227 (access: 30.01.2019).
[19] www.skyscrapercenter.com/building/56-leonard/844 (access: 31.01.2019).
[20] www.skyscrapercenter.com/building/eight-spruce-street/699 (access: 30.01.2019).
[21] www.skyscrapercenter.com/building/via-57-west/11584 (access: 31.01.2019).
[22] www.skyscrapercenter.com/city/new-york-city (access: 30.01.2019).
[23] www.streeteasy.com/building/new-york-by-ghery (access: 30.01.2019).
[24] www.timeout.com/newyork/little-italy-and-nolita-neighborhood-guide (access: 30.01.2019).
[25] www.podroze.gazeta.pl/podroze/1,114158,5134006.html (access: 30.01.2019).

If you want to quote this article, its proper bibliographic entry is as follow: Twardowski M., Żabicka A., Campos Ros A., *Houses and skyscrapers of manhattan – a horizontal or vertical city?*, Technical Transactions, Vol. 9/2019, pp. 45–56.

TECHNICAL TRANSACTIONS 9/2019
CIVIL ENGINEERING

DOI: 10.4467/2353737XCT.19.102.10884
SUBMISSION OF THE FINAL VERSION: 27/08/2019

Dagmara Adamkiewicz
dagmara.adamkiewicz@gmail.com

Elżbieta Radziszewska-Zielina orcid.org/0000-0002-3237-4360
eradzisz@izwbit.wil.pk.edu.pl
Institute of Management in Construction, Cracow University of Technology

A housing market analysis for the city of Krakow

Analiza rynku nieruchomości mieszkaniowych w mieście Kraków

Abstract

This article presents the results of a housing market analysis for the city of Krakow. The market study was performed in May 2019 using the online survey method on a group of 104 persons who were currently searching for an apartment. Based on initial studies, the authors analysed the opinions of potential customers, identified the apartments enjoying the highest demand, described the preferences of potential buyers and the criteria that encourage buying real estate to the greatest extent. Based on the results of the study, it can be concluded that the perceived need for persons to have their own apartment is the most common reason for purchasing a property. The most desirable housing has between 40 and 60 square metres of usable floor area, is composed of three rooms, in addition to a kitchen and a bathroom, and has its own dedicated parking space.

Keywords: housing market, preferences, Krakow

Streszczenie

W artykule przedstawiono wyniki badań dotyczące analizy rynku nieruchomości mieszkaniowych w Krakowie. Badania rynku zostały przeprowadzone metodą ankiety internetowej w maju 2019 roku na grupie 104 osób aktualnie poszukujących mieszkania. Na podstawie przeprowadzonych badań pierwotnych autorzy przeanalizowali opinie potencjalnych klientów, wskazali, na jakie mieszkania jest największe zapotrzebowanie, opisali preferencje potencjalnych nabywców oraz kryteria, które najbardziej zniechęcają do zakupu nieruchomości. Z wyników badań wynika, że potrzeba posiadania własnego mieszkania jest najczęstszym powodem kupna nieruchomości. Najbardziej pożądane mieszkanie ma od 40 do 60 m^2, składa się z trzech pokoi, kuchni i łazienki oraz posiada własne miejsce parkingowe.

Słowa kluczowe: rynek nieruchomości mieszkaniowych, preferencje, Kraków

1. Introduction

Studies associated with the real estate sector have been conducted all over the world for many years. Using the regression model, Tsai, Chang & Tzang [15] studied how external factors such as economic growth and taxation affect apartment prices in Taiwan. Similar studies were conducted in Italy investigating whether the introduction of real estate taxes had weakened the construction sector [3]. Housing demand in northern France has also been investigated [7]. Housing development must take into consideration the needs and demands of potential apartment buyers. Numerous studies concerning the preferences of residents have been performed. Farraz & Barus [6] investigated the housing preferences of the residents of Depok, Indonesia through the collection of data using survey and interview methods. Location can be defined using various methods, either with regard to the actual geographical location, or relative to other sites and places. As Heyman & Sommervoll [10] pointed out on the example of Oslo, relative location has a direct influence on the price of houses. Furthermore, Zhang, Zhou, Hui & Wen [16], when analysing apartment price data in the area of influence of the West Intime shopping mall in Hangzhou, demonstrated the impact of the distance from the analysed shopping mall on housing prices. A similar study was performed by Rivas, Patil, Hristidis, Barr & Srinivasan [12], who analysed the impact of the location of universities and hospitals on the local real estate markets; after analysing apartment prices for a period of seven years, they demonstrated that the proximity of these buildings causes a significant increase in property prices. Affuso, Caudill, Mixon & Starnes [1] assessed the impact of noise levels within the area of an airport in the United States on property value. Del Giudice, De Paila, Francesca, Nijkamp & Shapira [5] developed a decision-making support system for choosing properties based on key factors that define the attractiveness of a property.

The real estate sector in Poland has also been the subject of numerous studies and analyses. Kowalczyk, Kil & Kurowska [11] analysed the dynamics of change in the urban spaces of Polish cities. Szczepańska [13] used the example of Olsztyn to analyse the impact of real estate market processes on the selection of a place of residence. Various needs of potential buyers have also been analysed for many years. Głuszak & Marona [9] discussed the link between the socio-economic characteristics of apartment buyers and their property choices concerning geographical location. They developed a discrete model that studies housing preferences that affect the selection of apartment locations in Krakow. Gluszak [8] conducted a cycle of studies of housing demand and preferences in Krakow over a period of six years using the regression model to demonstrate a link between neighbourhood amenities and housing prices. On the example of Krakow, Butryn & Preweda [4] analysed the primary real estate market in the context of parking spaces. Public transport in large urban agglomerations is one of the main means of travel for many people; this was studied by Trojanek & Głuszak [14] who analysed the impact of the presence of the underground railway on housing prices using the example of Warsaw. They found proof that the presence of a rapid urban railway has a direct affect upon the value of nearby real estate.

The effectiveness of the use of marketing tools in real estate trading was described by Belniak & Radziszewska-Zielina [2], which included a presentation of an analysis of various marketing tools, the frequency of their use and the effectiveness of marketing measures. The authors of this study used primary data that was obtained using a survey.

The goal of this study was the analysis of the housing market. The study focused on Krakow, an agglomeration with a population of 750 thousand people that constitutes one of the largest Polish academic and cultural centres. It presents the results of a survey concerning the preferences of potential apartment buyers. The most desirable apartment locations, the characteristics of a perfect property and the criteria that encourage the purchase of a dwelling are indicated.

2. Research methods

An online survey study was performed in May 2019. The research tool that was used was an online questionnaire, a link to which had been posted on online portals frequented by persons searching for an apartment in Krakow. The questionnaire featured closed questions and a section that provided with information concerning respondents. It was constructed using questions which had either a nominal or an ordinal scale which was used by respondents to determine the significance of criteria and factors affecting property purchases, as well as an it was using interval scale which was used by to order the criteria according to size and dimension to appropriate sets. The study was conducted using nonprobability sampling, with the target group displaying specific traits. These were persons who declared a desire to purchase property in the near future in the city of Krakow, and were interested in both the primary and secondary markets.

The study was designed to identify which apartments were the most likely to be selected by buyers and was used to procure knowledge of client preferences concerning housing standards and location. The study aided in characterising the group of people generating demand and made it possible to determine the key criteria during the selection of a property, as well as those that encourage property purchases. The analysis of the results of the study identified the most desirable of Krakow's districts in terms of housing and also indicated which location displayed the greatest attractiveness. The studies helped to define the differences between the apartment preferences with regard to the motive behind their purchase.

3. Results

3.1. Respondent characteristics

The sample was composed of 104 persons, 65% were women and 35% were men. Effective demand supported by financial means was formed primarily by young persons with a higher education who were gaining professional experience and had an average or above-average income. The most numerous group among the respondents was comprised of persons below 30 years of age, constituting as much as 75% of all respondents. Of the persons comprising the sample, 16% were in the 31-40 age group, with persons above 41 years of age constituting 5%. The greatest interest in the real estate market was displayed by persons forming two-person households (47%), with persons in a three-person family model comprising 20% of respondents and 19% of the sample being comprised of single-person households. The remaining respondents (14%) were a part of large families, comprised of four or more members.

Within the housing property market, we can distinguish the primary market, in which 62% of respondents reported, and the secondary market, in which the remaining 38% were interested.

3.2. Preferred location

Apartment prices and interest in the property sector were highly varied and were dependent upon the area of the city. This was confirmed by secondary studies conducted on the basis of data published by the National Bank of Poland. This data concerns both listed and transaction prices per square metre of usable apartment floor area. The data stated that the most expensive properties were in the centre of Krakow, in the Stare Miasto, Grzegórzki and Prądnik Czerwony districts. These districts are characterised by compact development, with numerous townhouses and historical buildings, with their attractive locations significantly increasing the property value. Prices in these areas were high, even exceeding 10,000 PLN/m^2. The western area of the city – Krowodrza – was also characterised by high property prices. Nowa Huta has been the area with the cheapest apartments for many years.

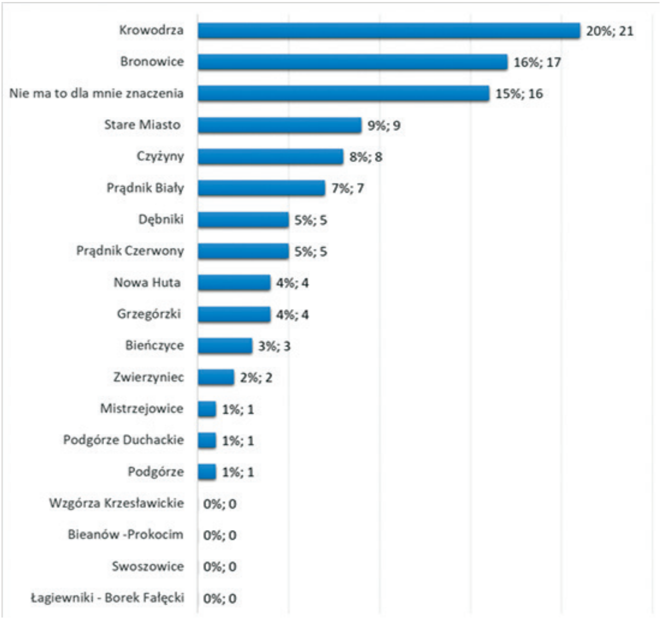


Fig. 1. Respondent interest in the various areas of Krakow in terms of the location of residential properties (by authors)

The respondents were asked to indicate the district of Krakow in which they would like to purchase an apartment. Interest in the individual districts is presented in Fig. 1. The results of the study indicate that the respondents displayed the greatest interest in the Krowodrza and Bronowice districts (20% and 16%, respectively). Stare Miasto, a district located in the central part of the city, was reported as preferred by 9% of respondents. It was claimed by 15% of respondents that the district in which they were to buy their property did not matter to them. The respondents showed no interest in the following districts: Wzgórza Krzesławickie, Bieżanów-Prokocim, Swoszowice and Łagiewniki-Borek Fałęcki.

3.3. Motivation behind the purchase of property

More than a half of the respondents (52%) reported that they were renting an apartment or a room in an apartment at the time of filling out the survey; 24% reported owning an apartment or a house, 19% reported living with their parents, and only 5% of respondents declared their current inhabited to be a hall of residence for students.

The motivations for the purchase of property were varied, affected mostly by the respondents' current personal, professional and financial situation, with the reported motives for the purchase of property presented in Fig. 2. The group of respondents reporting the need to have their own apartment as the reason for the purchase of property was the largest (43%). Respondents wanting to purchase property in order to invest money amounted to 20%. These persons were often over 30 years of age and were characterised by significant financial means at their disposal and the ownership of at least one piece of property – a house or an apartment that they resided in – with the purchase of an apartment being considered as a form of increasing their wealth.

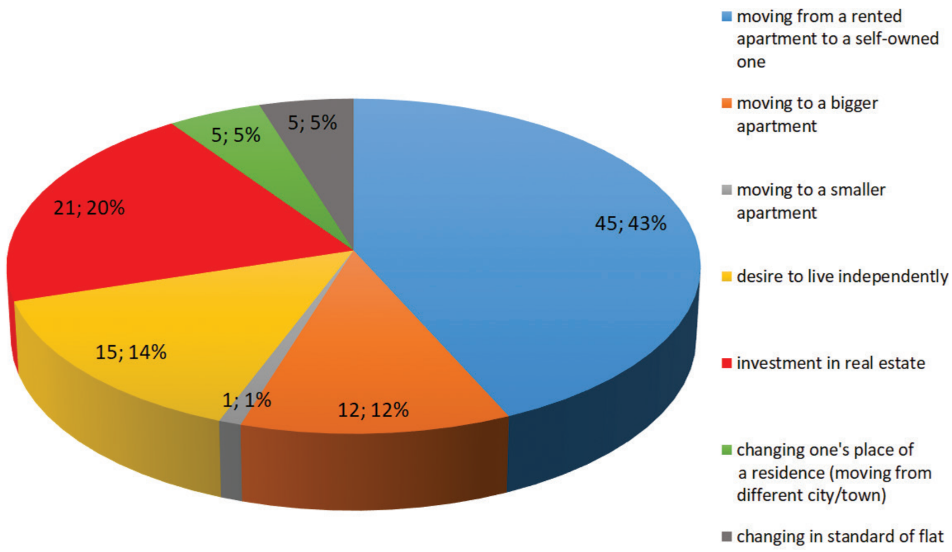


Fig. 2. Motivations for purchasing property as reported by respondents in the city of Krakow (by authors)

3.4. Preferences stated by respondents

Respondent property preferences were varied and were largely dependent upon the given apartment buyer's individual needs and capabilities.

The study performed by the authors demonstrated that the highest demand was for medium-sized apartments, with potential buyers showing the greatest preference for properties in tall buildings that are up to ten storeys in height (60% of respondents), while interest in buildings of up to four storeys was declared by 34% of the respondents, with 6% of respondents declaring a willingness to purchase an apartment in a building with more than ten storeys. The respondents declared the greatest willingness to purchase an apartment on the first (for the benefit of American readers, 'first' refers to the floor that is one storey above ground level), second or third floor (51%), with 35% of respondents showing interest in an apartment at a height between the fourth and tenth floors, 9% of respondents wanted an apartment on the ground floor, and 5% of respondents wanted an apartment located above the tenth floor.

Purchasing a property can be funded in various ways, with 71% of respondents choosing a mortgage, 28% of respondents choosing personal savings, while one person declared funding an apartment purchase through borrowing money from friends and family. The price of property was not reported to be seen as an indicator of its value, but it often made it unattainable for buyers, with 65% of the respondents wanting to allocate between 300 to 500 thousand PLN for this purpose. Those interested in cheaper apartments (up to 300 thousand PLN) accounted for 22% of respondents, with 8% of respondents aiming to allocate between 500 to 600 thousand PLN for the purchase, while 5% wanted to allocate more than 600 thousand PLN.

3.5. Criteria significance

During the survey, in addition to selecting the size of the preferred apartment, its location and the cost that the respondents were willing to pay for it, the significance of each criterion was reported and rated on a five-point scale (1 – the least important, 2 – not very important, 3 – important, 4 – very important, 5 – the most important). Figure 3 presents the average ratings by respondents concerning the significance of each criterion describing both the property itself and its location.

Price was reported as the most significant criterion during a purchase transaction, with the average rating given by respondents being around the 'very important' level, with a score value of 4.1. The layout of the apartment and the number of rooms or floor area were also criteria that were reported to have a very high impact on the selection of an apartment, with the average ratings being 4.0, 3.9 and 3.9, respectively. The least important and therefore the least desirable criteria were the inclusion of a living room kitchenette and a separate toilet. These solutions are declining in popularity among potential apartment buyers, particularly in the case of small apartments that do not include a separate bedroom. The average significance rating for these criteria was 'not very important' and its value for the living room kitchenette was 2.1, while for the separate toilet, it was 2.2.

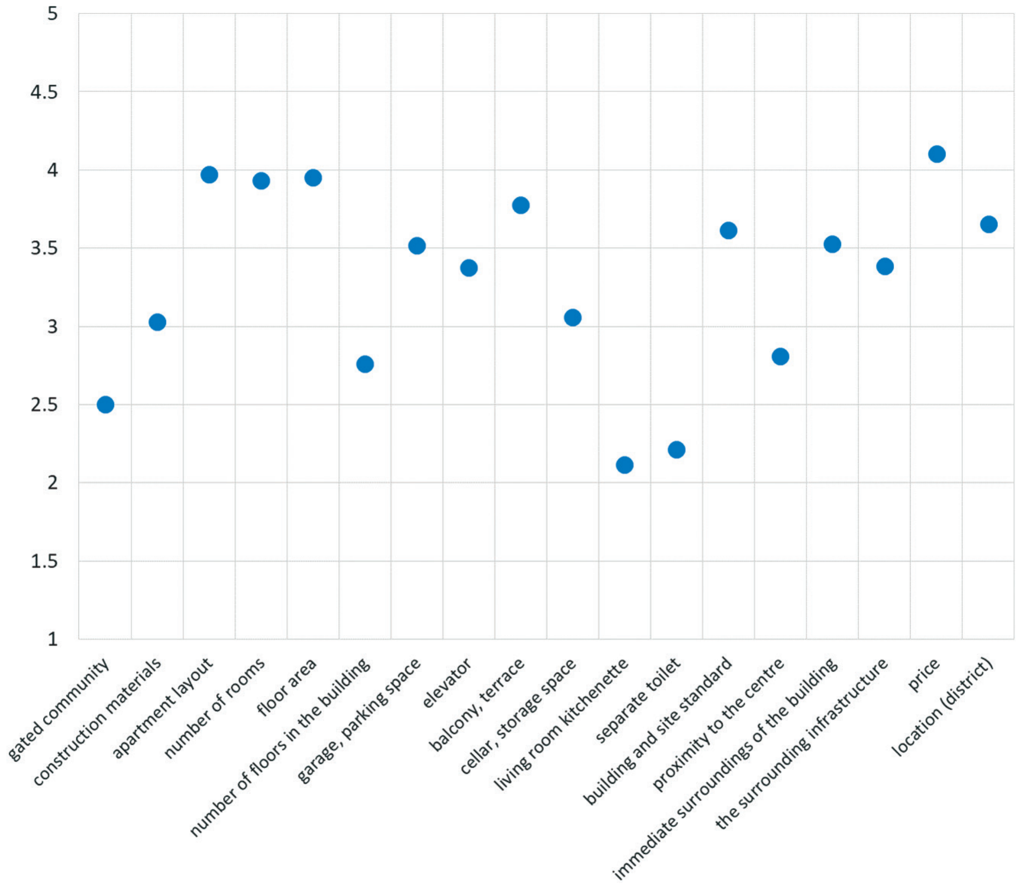


Fig. 3. Significance of individual criteria affecting the selection of a housing property (by authors)

3.6. Discouraging criteria

The respondents were also asked to identify criteria that dettered them from purchasing a housing property. Figure 4 features a listing with the criteria arranged in order from the most discouraging to least discouraging.

More than half of the respondents reported that a dangerous neighbourhood was a highly discouraging factor which considerably affected the selection of the location of an apartment to be purchased. A dangerous neighbourhood is understood as an area with a high crime rate, a lack of good illumination and visually unpleasant surroundings. The feeling of safety and comfort increases significantly when monitoring or security personnel are present. Limited public transport connections and property price were discouraging criteria for 38% of respondents, while 29% of respondents highlighted a lack of a parking space, with location being reported by 27%. The number of floors in the building, the lack of a cellar or underground storage space, as well as the construction materials that were used were reported to have a negligible impact on apartment selection.

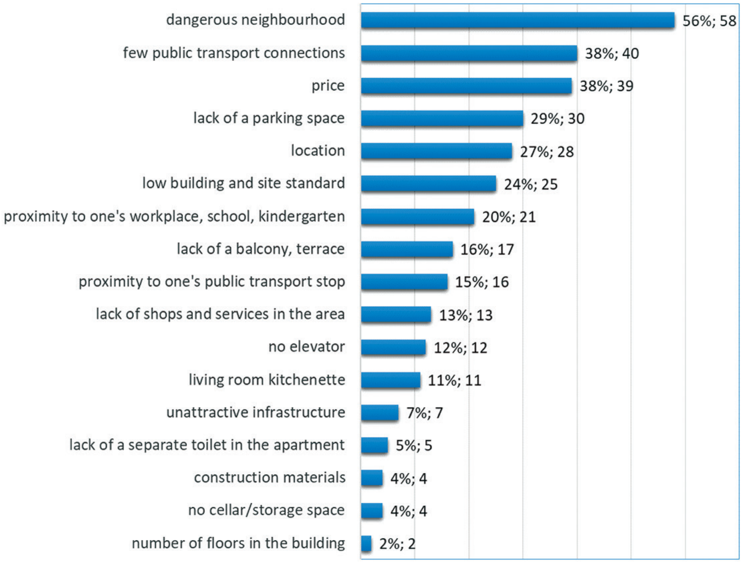


Fig. 4. The most discouraging criteria in the selection of a housing property (by authors)

3.7. Preferences of selected respondent groups

Depending on the developer, the same property can be perceived and used differently, and can therefore have different advantages and disadvantages, most significantly including its value. Figures 5 and 6 present the average significance ratings for criteria rated by various groups of people. The criteria affecting the selection of the location of a property were rated.

When comparing the answers given by men and women, we can conclude that both groups have similar requirements in terms of the property to be purchased; however, women rate most criteria higher. The price was the highest-rated criterion in both groups, with the average rating being 3.8 for women and 4.0 for men.

Respondents who searched for an apartment with the intention of moving into it had higher requirements in terms of both the apartments itself and its location. Among those who wanted to purchase property for rent, the most important criterion was accessibility to public transport and quick access to the city centre, which translates to higher attractiveness in the eyes of potential tenants. Considerable differences were observed in the case of proximity to one's place of employment, areas of greenery and a peaceful neighbourhood, with these factors being decidedly more important to future residents than for people who purchase in real estate for rent.

The least important criteria for all groups were the presence of a kindergarten, a school, shopping malls and stores, with their average significance rating amounting to a value of no higher than 2.5.

Criterion key for Figures 5 and 6:

1. Access to public transport
2. Quick access to the city centre

3. The presence of a nearby parking space
4. Proximity of green areas
5. Proximity to workplace
6. Proximity to a kindergarten or school
7. Proximity to shopping malls/stores
8. Peaceful neighbourhood
9. Noise level
10. Price

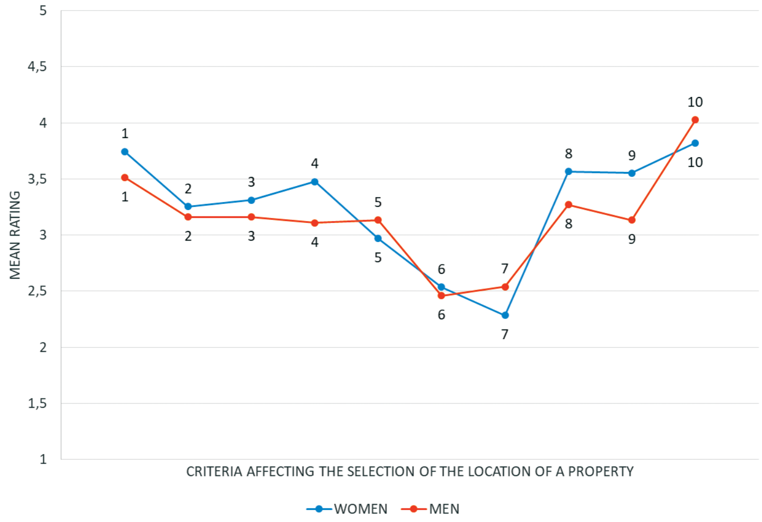


Fig. 5. Average ratings of individual criteria affecting the selection of the location of a property for both men and women (by authors)

Fig. 6. Average ratings of individual criteria affecting the selection of the location of a property for persons buying the property for themselves and investment buyers (by authors)

3.8. Apartment size preferences

Medium-sized apartments with a usable floor area of between 40 and 60 square metres were reported to attract the greatest amount of interest. However, upon a more precise verification of the database, we can observe a tendency for persons who see purchasing property as an investment to choose apartments that are smaller more frequently than those who are buying for their own needs or those of their loved ones. Figures 7 and 8 present the preferences of respondents concerning apartment size on the basis of the amount of usable floor area and the number of rooms.

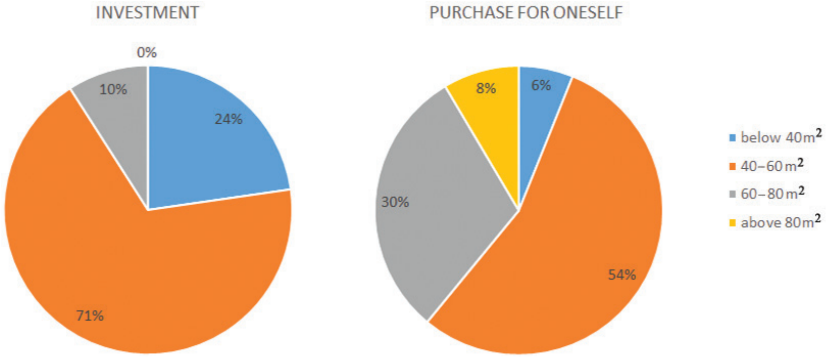


Fig. 7. Preferred usable floor area of the property versus the reason behind the property purchase (by authors)

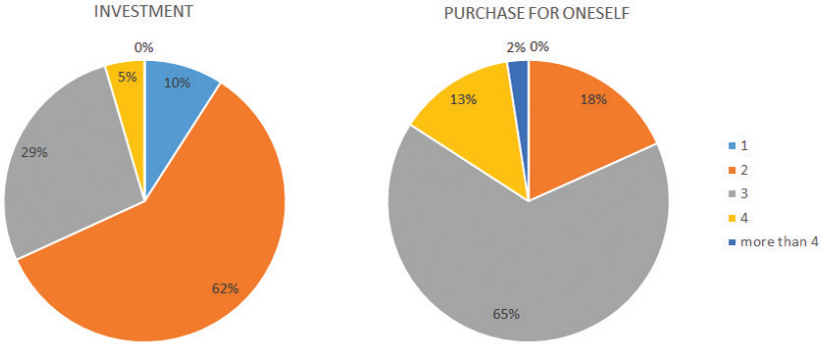


Fig. 8. Preferred number of rooms versus the reason behind the property purchase (by authors)

Persons who expressed a willingness to invest, and thus had the intention of renting out the property after purchase, most often selected two-room apartments (62%), with 10% choosing single-room studio apartments, while 29% preferred three-room apartments and 5% preferred four-room apartments. None of the respondents expressed interest in a large property with a floor area greater than 80 square metres or a four-room layout.

Among those purchasing the property for themselves, more than half (65%) preferred three-room apartments, while no one expressed interest in a studio. Two-room apartments were sought by 18% of the respondents, while a four-room apartment by 13%, with 2% of potential buyers looking for an apartment with more than four rooms.

4. Discussion

Owning real state is seen as an indicator of one's material status and position in society in both Poland and all over the world, which is why most dream of owning their own apartment or house, with ownership being one of their main life goals. Krakow is a city in which young persons create a demand on the real estate market. The purchase of property is often associated with entering marriage, which is why buyers are most often young, two-person households during their first phase of life who are yet to have children and the purchase of property is treated by them as a long-term investment. The main reason behind purchasing an apartment is to move to a self-owned apartment from a rented property, with the most-often selected form of financing the purchase being a mortgage. The study indicates that housing properties priced at between 300 and 500 thousand PLN that are of medium size and with a usable floor area of between 40 and 60 square metres were the most popular. The layout of the apartment is very important, as is appropriate insulation, the number of rooms and their plan. The apartments selected most often are comprised of three rooms, in addition to a kitchen and a bathroom. A balcony or a small terrace is a considerable asset, increasing the value of an apartment. However, fewer and fewer people are interested in a property where the living room features a kitchenette. A separate toilet is also something that is not seen as popular among persons looking for an apartment.

The study indicates that the relationship between the location and the price is highly significant, as is the presence of transportation nodes or tram and bus lines in the immediate vicinity which can provide quick access to the city centre and any facilities that are important to a potential apartment buyer. Another important and highly regarded aspect is the inclusion of one's own parking space. The aspect that was reported to be the largest deterrent to potential buyers was a dangerous neighbourhood, with buyers preferring a quiet and a peaceful neighbourhood, including a practical and functional arrangement of the space around the building, which also leads to an increased feeling of comfort and safety.

Persons who want to rent their property are more likely to select smaller, two-room apartments. In this case, it is important for the apartment to be located close to public transport links that can provide quick access to the city centre. Larger properties were selected decidedly more often by persons who were searching for an apartment for themselves. Close proximity to one's workplace and a peaceful neighbourhood in an area with low noise levels were valued considerably higher. The price was the most important criterion for all potential apartment buyers.

5. Conclusions

The survey study performed on a group of persons who were looking to buy property in Krakow indicates the preferences of potential buyers. The primary objective of the work was to identify the requirements that come into play during the search for an apartment, to define the group that creates the demand and to highlight the differences in requirements arising from the motivations behind the purchase of property. Analysis of the data revealed the most important criteria considered by buyers during the selection of a property and its location, including the most discouraging criteria.

Krakow's housing market is constantly developing, with developers building increasingly modern apartments, while more and more renovated and attractive apartments in townhouses appear on the secondary market; this situation enables everybody to find their dream apartment. The selection of a property is a decision that affects us over the long term and is affected by various factors, including financial capabilities and trends. In order to meet the requirements of clients, companies should pay particular attention to the preferences of potential buyers. As a result of adopting a stance that favours satisfying needs and appropriate marketing measures, developers are able to meet these requirements by developing their offering and becoming successful in the real estate sector.

Based on the results of the study, it can be concluded that the perfect apartment for the majority of buyers has between 40 and 60 square metres of usable floor area, is composed of three rooms, in addition to a kitchen and a bathroom, and has its own dedicated parking space. Such apartments should be located in ten-storey buildings, on the first, second or third floor, and be in close proximity to transportation nodes. In order to increase security, the building and its neighbourhood should be monitored and be equipped with an alarm system. Potential apartment buyers are prepared to pay more for a property that meet all of these requirements. The study is an important indication for developers, who can increase the prices of the apartments for which the demand is highest.

References

[1] Affuso E., Caudill, S.B., Mixon F.G., Starnes K.W., *Is Airport Proximity an Amenity or Disamenity? Empirical Investigation Based on House Prices*, Univ Wisconsin Press, Journal Division, 2019.

[2] Belniak M., Radziszewska-Zielina E., *Effectiveness of Applying Marketing Tools in Real Estate Trading*, IOP Conference Series: Materials Science and Engineering 471(11), 112074, 2019.

[3] Bimonte S., Stabile A., *The impact of the introduction of Italian property tax on urban development: a regional regression model*, Routledge Journals, 2019.

[4] Butryn K., Preweda E., *The primary market of parking places against the background of the primary housing market and planning policy on the example of Krakow*, International Conference on Environmental Engineering, ICEE, 2017.

[5] Del Giudice V., De Paola P., Francesca T., Nijkamp, P.J., Shapira, A., *Real Estate Investment Choices and Decision Support Systems*, MDPI, 2019.

[6] Farraz M.A., Barus L.S., *Housing Preferences and Choice Young Families Commuters in Depok City*, Indonesia, IOP Conference Series: Earth and Environmental Science 264(1), 2019.

[7] Flambard V., *Demand for housing choices in the north of France: a discrete approach*, Emerald Group Publishing LTD, 2017
[8] Głuszak M., *Externalities and house prices: A stated preferences approach*, Entrepreneurial Business and Economics Review 6(4), 2018, 181–196.
[9] Gluszak M., Marona B., *Discrete choice model of residential location in Krakow*, Journal of European Real Estate Research 10(1), 2017, 4–16.
[10] Heyman A.V., Sommervoll D.E., *House prices and relative location*, Cities 95, 2019.
[11] Kowalczyk C., Kil J., Kurowska K., *Dynamics of development of the largest cities – Evidence from Poland*, Cities 89, 2019, 26–34.
[12] Rivas R., Patil D., Hristidis V., Barr J.R., Srinivasan N., *The impact of colleges and hospitals to local real estate markets*, Journal of Big Data 6(1), 7, 2019.
[13] Szczepańska A., *Residential property market in the functional urban area of Olsztyn in the context of demographic changes*, Real Estate Management and Valuation 25(3), 2017, 30–39.
[14] Trojanek R., Gluszak M., *Spatial and time effect of subway on property prices*, Journal of Housing and the Built Environment 33(2), 2018, 359–384.
[15] Tsai Y.S., Chang C.P., Tzang S.W., *Demographic Structure, Business Fluctuations, Tax Shock and Housing Bubbles*, Advances in Intelligent Systems and Computing 994, 2019, 727–737.
[16] Zhang L., Zhou J., Hui E.C.M., Wen H., *The effects of a shopping mall on housing prices: A case study in Hangzhou*, International Journal of Strategic Property Management 23 (1), 2019, 65–80.

TECHNICAL TRANSACTIONS 9/2019
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.19.097.10879
SUBMISSION OF THE FINAL VERSION: 19/08/2019

Dalia Bednarska orcid.org/0000-0002-2146-2650
dalia.bednarska@p.lodz.pl

Marcin Koniorczyk orcid.org/0000-0002-6887-4324
Department of Building Physics and Building Materials, Lodz University of Technology

Cement paste microporosity analysis: a comparison of different experimental techniques

Analiza mikroporowatości zaczynu cementowego: porównanie metod eksperymentalnych

Abstract

Microstructure defines almost all material physical properties of a substance. Thus, its proper identification is essential for the assessment of material durability. Porous materials constitute the vast majority of those applied in civil engineering. The most important parameters describing a porous structure are the specific surface area, the shape and volume of pores and the pore size distribution. There are several methods which provide such results; however, each of them has some drawbacks. The main purpose of this paper is to compare results obtained by means of various methods commonly applied to the investigation of microstructure. These methods are mercury intrusion porosimetry (MIP), low temperature sorption of nitrogen and thermoporometry (TPM). The experimental research is conducted on aluminium oxide, which is characterised by unimodal pore size distribution and hardened cement paste prepared using portland cement (CEM I 42.5R with water-cement ratio equal to 0.5. The results obtained by the above-mentioned methods are thoroughly described and compared in this paper. Each of the presented approaches has some limitations; therefore, in order to receive a reliable description of porous microstructure, one has to apply at least two different experimental methods.

Keywords: porous materials, porous structure, cement paste, mercury intrusion porosimetry, low temperature nitrogen adsorption, thermoporometry

Streszczenie

Wśród materiałów budowlanych przeważającą większość stanowią materiały porowate. Dokładna znajomość mikrostruktury jest kluczowa w ocenie ich wytrzymałości i trwałości. Istnieje wiele metod eksperymentalnych służących do analizy struktur porowatych. W niniejszym opracowaniu porównane zostały następujące techniki: porozymetria rtęciowa (MIP), niskotemperaturowa adsorpcja azotu oraz termoporometria (TPM). Badaniom eksperymentalnym poddano dwa materiały. Pierwszy z nich, tlenek glinu, jest materiałem referencyjnym o unimodalnym rozkładzie porów. Zgodnie z deklaracją producenta dominująca średnica porów wynosi 7.3 nm. Drugim zastosowanym materiałem jest zaczyn cementowy przygotowany na bazie cementu portlandzkiego CEM I 42,5R. Stwardniały zaczyn charakteryzuje się skomplikowanym rozkładem porów. Opisane techniki analizy mikrostruktury są komplementarne. Aby uzyskać wiarygodny opis struktury wewnętrznej materiałów o skomplikowanym rozkładzie porów należy zastosować co najmniej dwie metody badawcze.

Słowa kluczowe: materiały porowate, struktura porowata, zaczyn cementowy, porozymetria rtęciowa, niskotemperaturowa adsorpcja azotu, termoporometria

1. Introduction

Microstructure defines almost all material physical properties of a substance. Thus, its thorough identification is crucial with regard to the proper assessment of its durability and endurance. Most of the materials used in civil engineering are porous. Concrete, probably the most commonly used building material worldwide, is characterised by a highly complex porous microstructure. The porosity of the contact zone between the aggregate and hardened cement paste significantly differs from the structure of the inner mass of cement paste [1]. Moreover various types of pores can occur in hardened cement paste, i.e. closed voids, so-called ink bottle pores and continuous voids. The latter greatly influence the transport properties of concrete. Porous materials are strongly prevalent among those applied in civil engineering. It is crucial to become thoroughly acquainted with the material microstructure in order to understand the formation and potential use of the investigated substance as well as to develop precise prediction models.

Porous material microstructure is defined by parameters such as specific surface area, cumulative pore volume and pore size distribution. Several methods are applied in order to obtain such results. One of these, the mercury intrusion porosimetry (MIP) technique, is commonly acknowledged as the standard method with regard to hardened cement paste. However, due to some limitations, it does not provide a complete insight into its microstructure. MIP enables the investigation of pores in the range of from 3.5 nm to 500 μm [2], when in reality, this technique is usually employed to study macropores[3]. The method is based on the assumption that each pore is connected to the material surface either directly or through larger voids. This results in the underestimation of larger internal pores preceded by narrow channels (ink-bottle pores) [4, 5]. The next applied experimental technique of material microstructure assessment is low temperature nitrogen adsorption [6]. Thus far, many empirical and physical formulas describing sorption data have been introduced, among which, the BET model is the most popular [7]. Although the BET model has been submitted to much criticism, it is widely used to determine the surface area and is recognised as a reference method. It assumes that adsorbate particles do not influence each other but do adsorb on a surface in several layers. However, a similar problem as in the case of MIP arises – due to the diameter of nitrogen particles, they are often excluded from ink-bottle pores, which disturbs the accuracy of results [8]. Additionally, large mesopores correspond to a narrow range of relative pressure, which is why they are often measured with insufficient precision [9]. Thermoporometry (TPM) is another method which enables the investigation of material porosity [10]. This is a relatively new technique based on the fact that liquid in pores freezes at a much lower temperature than bulk liquid. The temperature decrease depends on the size of the saturated pore. This relation is described by the Gibbs-Thomson equation [11]. In TPM, samples of a few milligrams are measured using a calorimeter, which results in a fast and low-cost analysis. Water is a common choice as far as a probe liquid in TPM is concerned; its relatively large heat of fusion leads to high sensitivity of the calorimetry curve. However, it is observed that during pore liquid freezing there exists a non-freezable layer of thickness of up to 2 nm, which can affect the accuracy of results [12]. This paper aims to investigate the porous microstructure of hardened cement paste through various experimental methods. Our intention is to compare results obtained by means of mercury intrusion porosimetry (MIP), low temperature sorption of nitrogen and thermoporometry (TPM).

2. Experimental methods

The mercury intrusion porosimetry technique is based on the premise that mercury, a non--wetting liquid, can be forced into pores of solid material only by applying external pressure. The relationship between pressure and the diameter of equivalent cylindrical pore, into which mercury is pressed at a given pressure, is described by the Washburn equation [12]:

$$d = -\frac{4\gamma\cos\theta}{P} \tag{1}$$

where:

P – the external pressure,
d – the pore diameter,
γ – the surface tension,
θ – the contact angle.

The MIP analysis is conducted by means of Micromeritics AutoPore IV9500 apparatus. The investigation is performed on coreshaped samples of a representative volume of cement paste (10 mm in diameter and 15–20 mm in length).

The second method applied is N_2 nitrogen adsorption/desorption. The analysis is performed at the temperature of liquid nitrogen (approx. 77 K) by means of a Micromeritics ASAP 2020 device. Firstly, the sample has to be outgassed. Secondly, consecutive portions of adsorbate are supplied to a crucible containing the specimen and the system is enabled to attain a state of equilibrium. As a result, nitrogen adsorption/desorption isotherms are created. In order to estimate the specific surface area, the BET model is applied in the presented paper. This approach is based on the following expression [13]:

$$\frac{1}{v\left[\left(\frac{p_0}{p}\right)-1\right]} = \frac{c-1}{v_m c}\left(\frac{p}{p_0}\right) + \frac{1}{v_m c} \tag{2}$$

where:

p – the equilibrium pressure,
p_0 – the saturation pressure of the adsorbate,
v – the adsorbate quantity,
v_m – the adsorbate volume, when it covers the adsorbent as a monolayer.

BET theory assumes that gas particles can embed in the surface in several layers, but every layer above the first is characterised by liquid-like properties. Pore size distribution is determined according to Barrer, Joiyner and Halenda theory (BJH), which is based on the Kelvin equation concerning capillary condensation in mesopores [14]:

$$\ln\left(p/p_s\right)=\frac{-2\gamma w_m \cos\theta}{RTr_c} \tag{3}$$

where:

- θ – the surface tension,
- w_m – the molar volume,
- γ – the contact angle.

The method is acknowledged as a standard method especially in North America. The theory is based on the premise that during capillary condensation (i.e. for relative pressure larger than 0.4), the pressure increase causes a thickness increase of the adsorbate layer located on the pore walls. On the basis of the estimated thickness, the diameter of the equivalent cylindrical pore is determined.

Phase transitions are connected to heat effects. During freezing, energy is released whereas in the case of melting, energy needs to be provided. The measurement of the net heat exchanged with surroundings enables assessment of the progress of any endo or exothermic process. This fact associated with temperature decrease during freezing/thawing in confined space is the foundation of the thermoporometry technique. The relationship between the liquid-solid transition temperature and the interface curvature considering the triple point of a pure substance was introduced by Defay et al. [11]. If one assumes that the chemical potentials of water and ice remain in equilibrium and that pores are of a cylindrical shape, then by applying the Laplace equation describing the mechanical equilibrium at the interface, the following depression temperature formula can be obtained:

$$\Delta T_m = \frac{2T_0\gamma_{sl}}{\rho_l \Delta H_f}\frac{\cos\theta}{r_p-\delta} \tag{3}$$

where:

- T_0 – the melting temperature of the bulk state,
- γ – the solid/liquid surface tension,
- ρ_l – the liquid density,
- r_p – the radius of the pore,
- δ – the thickness of the unfrozen water film,
- θ – the contact angle.

The above relationship is the so-called Gibbs-Thomson equation. This formula is commonly applied in order to determine the pore size distribution on the basis of the DSC curve [15, 16, 17]. In the literature, numerous variations of the Gibbs-Thompson equation can be found which express pore radius as a function of overcooling temperature. These can be obtained either through the approximation of system parameters [10] or as empirical relationships which reflect the experimental data [17]. The most important of such relationships is that introduced by Brun [10], which is presented in Table 1.

Table 1. Relationship between pore radius and overcooling temperature introduced by Brun

Freezing	$r_P(\mathrm{nm}) = -\frac{64.67}{\Delta T} + 0.57$
Melting	$r_P(\mathrm{nm}) = -\frac{32.33}{\Delta T} + 0.68$

The other commonly applied example is that proposed by Landry [18], who derived it on the basis of experimental data. He also introduced formulas for pore diameter for both freezing and melting (see Table 2).

Table 2. Relationship between pore radius and overcooling temperature introduced by Landry

Freezing	$r_P(nm) = -\frac{38.558}{\Delta T - 0.1719} + \delta_f$
Melting	$r_P(nm) = -\frac{19.082}{\Delta T + 0.1207} + \delta_m$

where $\delta_f = 0.04$ nm and $\delta_m = 1.12$ nm.

The differential scanning calorimetry (PerkinElmer DSC 4000) is used to measure the heat released during water solidification.

3. Results

The experimental research was conducted on two kinds of material. Firstly, aluminium oxide was investigated as a material characterised by unimodal size distribution. Secondly, the hardened cement paste as an actual building material is studied.

3.1. Aluminium oxide

The applied material is a porous, amorphous, granular form of aluminium oxide. It is supplied by Norton Chemical Process Products Corp., Akron. According to the producer's declaration, it is characterised by unimodal pore size distribution, specifically, the dominant pore size is 7.3 nm and the porosity is 0.56 ml/g. The chemical composition (% wt) of the material, according to producer's information, is as follows: aluminium oxide (99.7–99.9), silicon dioxide (0.1–0.2), ferric oxide (0.1).

As mentioned in previous sections, the material microstructure was investigated by means of three methods: mercury intrusion porosimetry, low temperature N_2 adsorption/desorption and thermoporometry with water as a probe liquid. In the case of the MIP technique, the maximum pressure applied to the sample was 400 MPa. The test results are presented in Fig. 1. The pore size distribution and cumulative pore volume imply that the material microstructure actually consists of equivalent pores, the diameters of which are 7.3 nm. Additionally, within the MIP analysis, the following parameters were determined: pore volume was 0.560 ml/g, bulk density was 1.298 g/ml, skeletal density was 4.712 g/ml and the total porosity was 72.5%.

The results obtained by means of the nitrogen adsorption/desorption test are presented in Figs. 2 and 3. The shape of sorption isotherms (Fig. 2) is characteristic for IV type according to IUPAC classification, which is typical for mesoporous adsorbents. The hysteresis loop beginning at *p/p*° = 0.65 can be classified as A type as per de Boer [19], which implies cylindrical pores of relatively constant intersection. The regular sample microstructure is also confirmed by pore size distribution, which is characterised by one visible maximum (see Fig. 3). The specific surface area determined by the BET method was 190 m^2/g, the total pore volume was 0.58 ml/g and the average pore diameter was 7.78 nm.

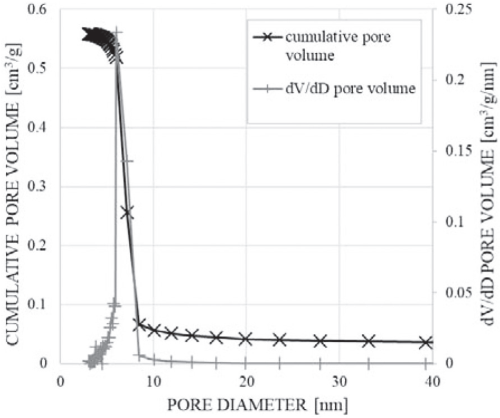


Fig. 1. Pore size distribution and cumulative pore volume of aluminium oxide obtained by the MIP technique

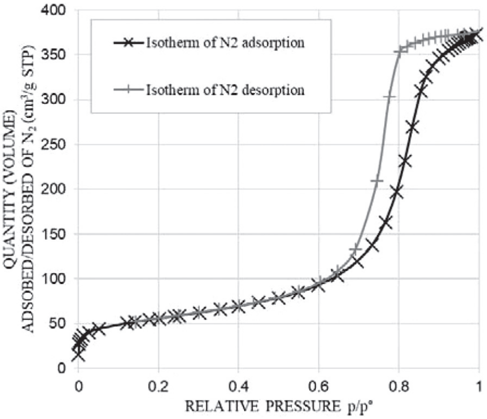


Fig. 2. N_2 adsorption/desorption isotherms determined for aluminium oxide

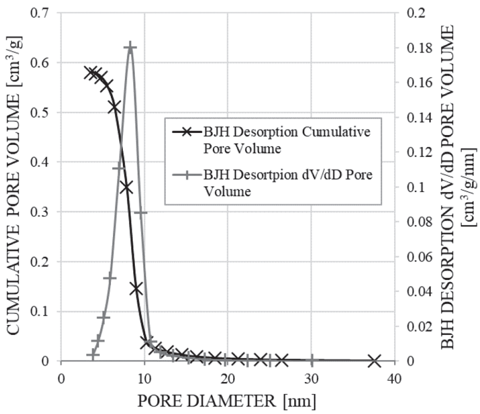


Fig. 3. Pore size distribution and cumulative pore volume of aluminium oxide obtained by low temperature N_2 sorption

The TPM analysis is conducted for DSC scan with slow cooling/heating rate, which is 0.1°C/min. Such a temperature rate allows the sample to remain in a state of thermal equilibrium. The calculations are conducted in accordance with Brun and Landry formulas. The obtained values are compared in Table 3. It is evident that results estimated on the basis of the Landry equation are more thorough in comparison to the producer's data.

Table 3. The average pore diameters of aluminium oxide calculated for the Brun and Landry relationships

	BRUN [nm]	LANDRY [nm]
Freezing	11.36	6.10
Melting	9.06	6.86

3.2. Cement paste

Hardened cement paste was the second material under investigation. The material was prepared from the Portland cement CEM I 42.5R with a water to cement ratio of 0.50. Samples were formed in small PVC moulds. After twenty-four hours, they were demoulded and cured for twenty-eight days in a water bath. Two kinds of samples were subsequently cut off from the initial specimens. Small cylinders with diameter 10 mm and height 15 mm were investigated by MIP as well as low temperature N_2 adsorption tests, whereas small discs (5 mm diameter and 3 mm height) were studied using the TPM method. Such dimensions guaranteed the homogenous, representative volume of the examined samples [20]. In the case of each sample, the proper analysis was preceded by the drying process at 30°C until the solid sample mass was obtained. The minimal pore radius possible to be detected by MIP method is 3 nm. Thus, this method enables investigation of both mesopores and macropores. The pore size distributions and cumulative pore volumes are presented in Fig. 4. The obtained results confirm that cement paste has a highly complex structure. As a result of MIP tests, the following sample parameters were determined: pore volume was 0.150 ml/g, bulk density was 1.618 g/ml, skeletal density was 2.120 g/ml and total porosity was 23.7%.

The shape of sorption isotherms obtained by means of low temperature N_2 adsorption (Fig. 5) is typical for mesoporous and macroporous materials. The hysteresis loop begins at a much lower relative pressure for cement paste than for alumina oxide. Such a loop shape implies the presence of ink-bottle pores in hardened cement paste [21]. The BET surface area was 12.510 m^2/g, and the total pore volume was 0.070 ml/g. The cumulative pore volume was nearly two times lower than that determined by the MIP test, which was caused by insufficient estimation of the larger pores (see Fig. 6).

As far as TPM method is concerned, the same experimental procedure as in the case of aluminium oxide was applied. The results according to Brun and Landry equations are presented in Table 4. and in Fig. 7. It can be observed that pore size distributions obtained by two different methods have similar characters. In the case of hardened cement paste, results determined according to Landry's formula are more consistent with those from the MIP test.

Table 4. The average pore diameters of cement paste calculated for Brun and Landry relationships

	BRUN [nm]	LANDRY [nm]
Freezing	34.75	38.46
Melting	32.49	39.07

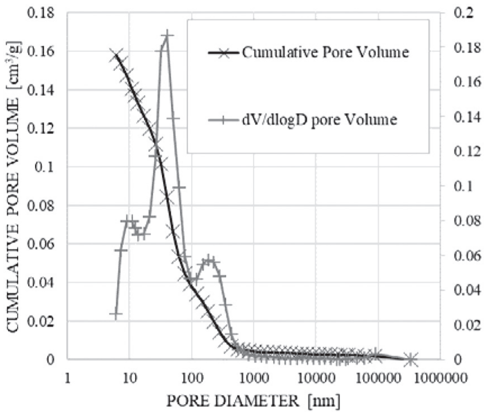


Fig. 4. Pore size distribution and cumulative pore volume of cement paste obtained by the MIP technique

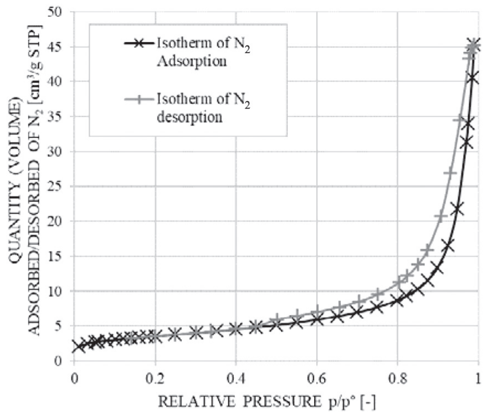


Fig. 5. N_2 adsorption/desorption isotherms determined for cement paste

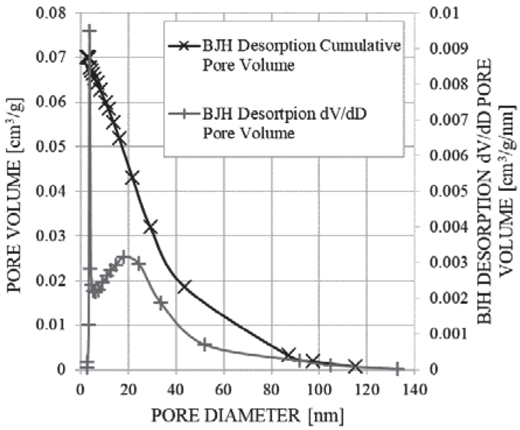


Fig. 6. Pore size distribution and cumulative pore volume of cement paste obtained by low temperature N_2 sorption

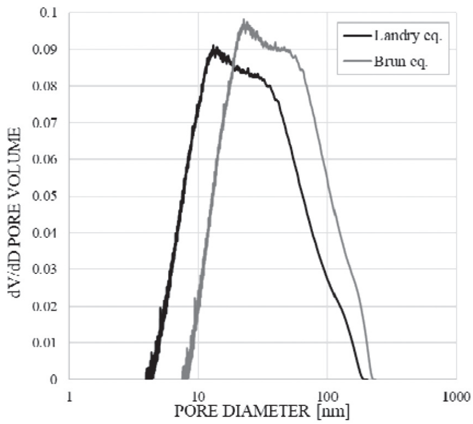


Fig. 7. Pore size distribution obtained by the thermoporometry technique

4. Conclusions

The main purpose of the paper is to compare various methods used in microstructure analysis. The analysis is performed on two kinds of samples. The first is silica alumina, which consists of equivalent pores. The second material, hardened cement paste, is characterised by complex pore distribution. Since such materials are characterised by a highly complex pore size distribution, a thorough examination of its structure is a challenging task. Each of the presented experimental methods have some drawbacks. For instance, before MIP or nitrogen sorption, samples need to be completely dried. Such a treatment can influence specimen microstructure. High temperature or moisture transport can induce strain and thus produce some micro-cracks, which change the initial pore size distribution. In the case of thermoporometry, a sample has to be fully saturated with a probe liquid and therefore problems connected to deterioration caused by sample preparation are reduced.

The experimental results obtained for aluminium oxide are consistent with data provided by the producer. The material microstructure consists of a framework with one dominant pore diameter, which is proven by nitrogen adsorption as well as the MIP technique. The dominant pore size obtained by the three various methods are in agreement with the producer's declaration. Despite the much more complex microstructure, the results obtained for hardened cement paste by the different methods are also relatively consistent with each other. Each of the presented techniques has some drawbacks. The most important issue which has to be taken into consideration before the choice of a proper experimental method is the range of pore sizes occurring in the sample microstructure. Each of described method presents the highest precision for a limited range of pore sizes. One should be aware that the presented methods are rather complementary. Thus, in order to receive a thorough and exact microstructure description, at least two different experimental methods should be applied.

References

[1] Neville A.M., *Właściwości betonu*, Pearson Education Limited, Kraków 2012.

[2] Giesche H., *Mercury Porosimetry: A General (Practical) Overview*, Particle & Particle Systems Characterization 23(1)/2006, 9–19.

[3] Léon y León C.A., *New perspectives in mercury porosimetry,* Advances in Colloid and Interface Science 76–77/1998, 341–372.

[4] Abell A.B., Willis K.L., Lange D.A., *Mercury Intrusion Porosimetry and Image Analysis of Cement-Based Materials*, Journal of Colloid and Interface Science 211(1)/1999, 39–44.

[5] Moro F., Böhni H., *Ink-Bottle Effect in Mercury Intrusion Porosimetry of Cement-Based Materials*, Journal of Colloid and Interface Science 246(1)/2002, 135–149.

[6] Sing K., *The use of nitrogen adsorption for the characterisation of porous materials*, Colloids and Surfaces A: Physicochemical and Engineering Aspects 187–188/2001, 3–9.

[7] Baroghel-Bouny V., *Water vapour sorption experiments on hardened cementitious materials: Part I: Essential tool for analysis of hygral behaviour and its relation to pore structure*, Cement and Concrete Research 37(3)/2007, 414–437.

[8] Garci Juenger M.C., Jennings H.M., *The Use of nitrogen adsorption to assess the microstructure of cement paste*, Cement and Concrete Research 31/2001, 883–892.

[9] Majda D., Ikonen T., Krupa A., Lehto V.-P., Makowski W., *Application of thermoporometry for characterization of mesoporous silicon: In search for probe liquid aimed at large pores*, Microporous and Mesoporous Materials 264/2018, 1–7.
[10] Brun M., Lallemand A., Quinson J.-F., Eyraud C., *A new method for determination the simultaneous of the size and the shape of pores: the thermoporometry*, Termochimica Acta 21(1)/1977, 59–98.
[11] Defay R., Prigogine I., Bellemans A., Everett D.H., *Surface tension and adsorption*, Wiley, New York 1966.
[12] Ishikiriyama K., Todoki M., Motomura K., *Pore Size Distribution (PSD) Measurements of Silica Gels by Means of Differential Scanning Calorimetry: I. Optimization for Determination of PSD*, Journal of Colloid and Interface Science 171(1)/1995, 92–102.
[13] Brunauer S., Emmett P.H., Teller E., *Adsorption of Gases in Multimolecular Layers*, Journal of the American Chemical Society 60/1938, 309–319.
[14] Barrett E.P., Joyner L.G., Halenda P., *The Determination of Pore Volume and Area Distributions in Porous Substances. I. Computations from Nitrogen Isotherms*, Journal of the American Chemical Society 73(1)/1951, 373–380.
[15] Jähnert S., Vaca Chávez F., Schaumann G.E., Schreiber A., Schönhoff M., Findenegg G.H., *Melting and freezing of water in cylindrical silica nanopores*, Physical Chemistry Chemical Physics 39/2008.
[16] Ishikiriyama K., Todoki M., *Evaluation of water in silica pores using differential scanning calorimetry*, Thermochimica Acta 256(2)/1995, 213–226.
[17] Ishikiriyama K., Todoki M., *Pore Size Distribution Measurements of Silica Gels by Means of Differential Scanning Calorimetry: II. Thermoporosimetry*, Journal of Colloid and Interface Science 171(1)/1995, 103–111.
[18] Landry M.R., *Thermoporometry by differential scanning calorimetry: experimental considerations and applications*, Thermochimica Acta 433(1–2)/2005, 27–50.
[19] de Boer J.H., *The Structure and Properties of Porous Materials*, Butterworth, London 1958.
[20] Zhang M.Z., Ye G., van Breugel K., *A numerical-statistical approach to determining the representative elementary volume (REV) of cement paste for measuring diffusivity*, Materiales de Construcción 300(60)/2010, 7–20.
[21] Sarbak Z., *Adsorpcja I Adsorbenty. Teoria i zastosowanie*, UAM Academic Publishing, Poznań 2000.

If you want to quote this article, its proper bibliographic entry is as follow: Bednarska D., Koniorczyk M., *Cement paste microporosity analysis: a comparison of different experimental techniques*, Technical Transactions, Vol. 9/2019, pp. 71–80.

TECHNICAL TRANSACTIONS 9/2019
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.19.098.10880
SUBMISSION OF THE FINAL VERSION: 19/08/2019

Magdalena Gicala orcid.org/0000-0003-7433-2130
mgicala@agh.edu.pl
Faculty of Mining and Geoengineering, AGH University of Science and Technology
Anna Halicka orcid.org/0000-0001-5526-8862
Faculty of Civil Engineering and Architecture, Lublin University of Technology

The influence of the demolition process on the environmental impact of reinforced concrete structures based on recycled aggregate

Wpływ procesu rozbiórki na oddziaływania środowiskowe konstrukcji żelbetowych z kruszywem pochodzącym z recyklingu

Abstract

The article presents an analysis of the influence of the demolition process on the environmental impact of a reinforced concrete structure, based on recycled concrete aggregate (RCA). Two aggregate production scenarios, varied in terms of the scope, were adopted and the contribution of RCA to the total environmental impact as well as the influence of demolition on the environmental performance of RCA were determined. The NONROAD model was used in the research as a tool for calculating the emissions generated by the equipment used for the processing of construction debris. Environmental impacts were assessed on the basis of the Ecopoint value. Despite the large quantity of aggregate in the concrete mixture, it did not constitute a significant environmental impact. However, demolition was the dominant process in the production of recycled concrete aggregate and it is reasonable to consider this process in an environmental analysis.

Keywords: environmental impact, recycled concrete aggregate (RCA), demolition, reinforced concrete structures

Streszczenie

W artykule przedstawiono analizę wpływu procesu rozbiórki na oddziaływania środowiskowe konstrukcji żelbetowej, do wykonania której zastosowano kruszywo z recyklingu betonu. Przyjęto dwa scenariusze produkcji kruszywa zróżnicowane pod względem zakresu i ustalono udział kruszywa w oddziaływaniach całkowitych konstrukcji oraz wpływ rozbiórki na efektywność środowiskową kruszywa. W badaniach wykorzystano model NONROAD jako narzędzie umożliwiające ustalenie emisji generowanych przez sprzęt służący do pozyskania i przetwarzania gruzu budowlanego. Oddziaływania środowiskowe oceniono na podstawie wartości wskaźnika Ecopoint. Pomimo przeważającej w stosunku do pozostałych składników ilości kruszywa w mieszance betonowej nie generuje ono istotnych oddziaływań środowiskowych. Sama rozbiórka jest natomiast procesem dominującym w produkcji kruszywa i zasadne jest uwzględnianie jej w analizie środowiskowej.

Słowa kluczowe: oddziaływania środowiskowe, kruszywo recyklingowe, rozbiórka, konstrukcje żelbetowe

1. Introduction

As concrete production is one of the main uses of natural raw materials, the use of concrete within construction significantly influences the demand for aggregates. This is a major challenge for the European mineral aggregates industry, which, in order to satisfy the demands of concrete production, should ensure an annual production of 2,700 million tonnes [21]. Due to the depletion of primary resources and energy-intensive extraction, excessive exploitation of aggregates is becoming a threat to the environment and a global economic problem [18]. However, the increasing amount of construction and demolition waste (C&D) requires the implementation of new waste-management concepts. An effective solution is the promotion of reverse logistics models based on a circular economy, in which the highest possible recovery of materials for re-use is promoted. In this way, debris that is a waste product from the demolition of structures can be used after mechanical processing as an aggregate in concrete production.

Research on the environmental aspects of the recycled concrete aggregate is most often based on the *cutoff* principle. This means omitting the impact of the primary aggregate production process and only considering the processes directly related to C&D waste management. The demolition phase is usually excluded from the analysis [9, 20]. However, research is also performed in which demolition is considered as the first step of recycled aggregate production, prior to the transport of debris to the processing plant or to the landfill as well as mechanical treatment processes [8]. This approach seems to be appropriate if it is considered that the concrete structure to be demolished plays the same role in the production of recycled aggregate as the mine in the case of natural, primary aggregates.

Despite the above-discussed, after the period of technical suitability for use, the demolition of a structure is conducted regardless of the possibility for the recovery, reuse or recycling of materials. According to the standard concept of the building life cycle [5], the demolition process belongs to the end of life stage, within the system boundary. Reconsideration of this phase in the analysis of environmental impacts generated during the production of recycled aggregate may therefore arouse controversy. However, the standard assumptions according to which the transport, waste processing and disposal are also within the boundaries of the previous system, the validity of the analysis of environmental impacts associated with the production of recycled aggregate may be in question.

The lack of consistency in the determination of the boundaries of the recycled aggregate production system observed in the research, encourages the conducting of comparative analyses; such analyses were performed in the article. This was carried out using the example of a beam as the basic structural element of a reinforced concrete structure.

2. Method

2.1. Subject of the research and assumptions

The three-span reinforced concrete beam which was the subject of the previous research of the authors was analysed. It is a beam with a rectangular cross section of dimensions $b = 0.25$ m, $h = 0.85$ m loaded with a permanent load of $g = 24$ kN/m (above the dead load), uniformly distributed over the beam length and a live load of $q = 30$ kN/m. The analysis of the structure was based on the linear elasticity theory and the calculation of the beam was performed in accordance with European Standard [4] for 5 load combinations with consideration to ultimate and serviceability limit states (ULS and SLS). A characteristic value of concrete strength of $f_{ck} = 40$ MPa was assumed. It was found that for the adopted diameter of Ø = 20 mm in the left and right spans ($l_1 = 5$ m) two bars should be applied whereas in the middle span ($l_2 = 7$ m) and supports, three bars should be applied. The total mass of steel was determined to be $m_s = 227.17$ kg.

The research concerned environmental impacts generated during the production of materials necessary to prepare the three investigated beams. The analysis covers two scenarios of the recycled aggregate production process (Fig. 1). The S1 scenario includes basic processes such as: demolition of the building, initial debris crushing, transport of aggregate and re-crushing in the plant using an impact crusher as well as the auxiliary processes of debris loading into the jaw crusher and aggregate loading onto the truck. The S2 scenario excludes only the demolition stage from the analysis, taking all other processes into account. Neither of the scenarios takes into account the potential for reusing materials without processing, waste disposal, transport of ingredients to the concrete plant and production of the concrete mixture as well as the subsequent life cycle stages of the new structure. For both scenarios, the processes are the same and do not affect the result of the comparative analysis.

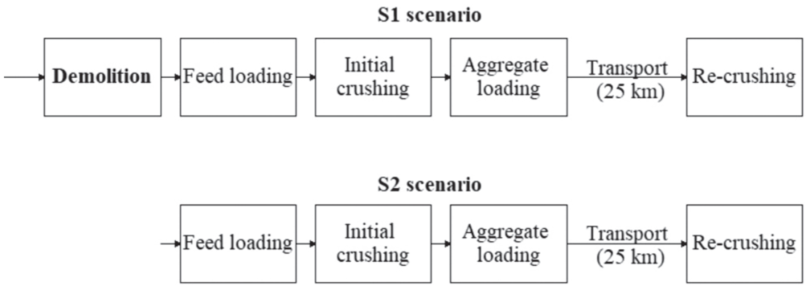


Fig. 1. Scope of the analyses within the considered scenarios of RCA production

2.2. Design of the recycled aggregate concrete mixture

The composition of the concrete mixture in which the natural aggregate was completely replaced with recycled concrete aggregate was analytically determined based on the recommendations included in [12]. It has been taken into account that the physical and mechanical properties of the recycled concrete aggregate are different from the properties of natural aggregate. The analysis considered the influence of the characteristic value of primary concrete strength on crushing strength correlated with recycled aggregate concrete properties (Fig. 2).

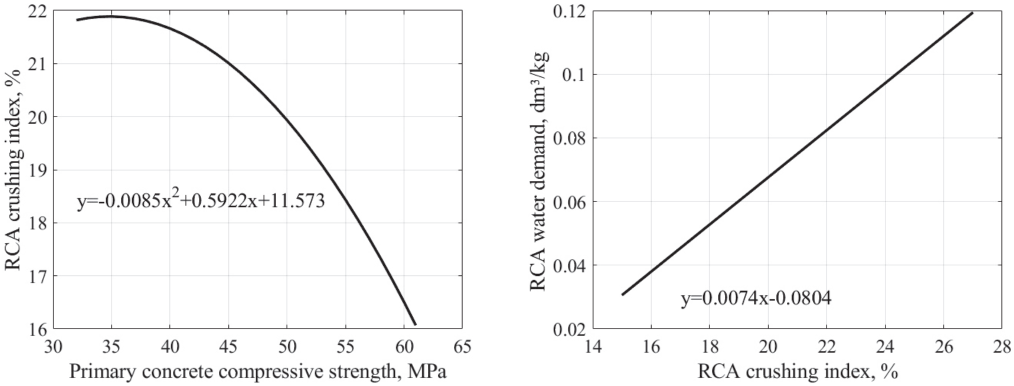


Fig. 2. Effect of primary concrete strength on the crushing strength (2a); the water-demand of RCA as a function of the crushing index (2b) [12]

It was assumed that the characteristic value of primary concrete strength was 55 MPa and using the relationships shown in Fig. 2, the crushing strength expressed by the crushing index $w_r = 18.43\%$ and the water demand of aggregate $w_{RCA} = 0.056$ dm³/kg were determined. On the basis of these parameters, the set of equations presented in Table 1 combining the content of individual components with the properties of a concrete mixture and hardened concrete was solved. It was assumed that the characteristic value of obtained concrete strength should be $f_{ck} = 40$ MPa and for this strength, the composition of the concrete mixture was determined. Apart from cement, water, fine aggregate (sand) and coarse aggregate, the concrete mixture did not contain admixtures or additives.

Table 1. Equations for designing the composition of a concrete mixture with recycled concrete aggregate according to the analytical method

Strength equation	$f_{cm} = A_{RCA} \cdot [(c/w) - 0.5]$
Robustness equation	$C/\rho_C + P/\rho_P + K_{RCA}/\rho_{RCA} + W = 1000$
Water demand equation	$W = C \cdot w_C + P \cdot w_P + K_{RCA} \cdot w_{RCA}$
Characteristic equation	$P_p = P/(P + K_{RCA})$
Symbols according to [12]: f_{cm} – mean strength, MPa; $f_{cm} = f_{ck} + 8$, Mpa, A_{RCA} equivalent of the coefficient A in the equation describing the strength according to Bolomey, $A_{RCA} = 49.14 - 34.46 \cdot (w/c) + 88.20 \cdot (w/c)^2 - 2.42 \cdot (w/c) \cdot w_r$; C, W, P, K_{RCA} amount of cement, water, fine aggregate (sand) and recycled concrete aggregate in the concrete mixture, kg/m³; P_p share of sand in aggregate, $P_p = 0.35$; w_C, w_P, w_{RCA} water demand of cement, sand and recycled concrete aggregate respectively, dm³/kg; w/c water to cement ratio; w_r – crushing index, %; $\rho_C, \rho_P, \rho_{RCA}$ density of cement, sand and recycled concrete aggregate, respectively, kg/dm³.	

Based on the above calculations, it was found that to achieve the assumed compressive strength, 1 m^3 of concrete mixture should contain 336.7 kg of cement, 187.5 kg of water, 639.9 kg of fine aggregate (sand) and 1,188.4 kg of recycled coarse aggregate. The use of recycled material as a fine aggregate was not taken into account because it is not recommended due to its high absorption [20].

2.3. Environmental impacts of cement, water, fine aggregate and reinforcing steel

Environmental performance was expressed using a set of indicators proposed by standard [5], for six environmental categories: global warming potential (GWP), acidification potential of soil and water (AP), eutrophication potential (EP), abiotic depletion potential for non-fossil resources (ADPE), formation potential of tropospheric ozone (POCP) and abiotic depletion potential for fossil resources (ADPF). Ozone depletion, which can be significantly affected by the processes of RCA production, especially the demolition process, was not taken into account. Due to the uncertainty of the data and the desire to present reliable analysis results, this category was omitted. In the study, only the environmental impacts of the first stage of the structure life cycle (product stage) relating to the production of the concrete mixture components and reinforcing steel are analysed.

Table 2 presents the values of the environmental impacts per unit of cement, water, fine aggregate (sand) and reinforcing steel amount, determined on the basis of Environmental Product Declarations (EPD).

Table 2. The values of environmental indicators in individual categories per unit of materials amount based on EPD

Environmental indicator	Cement [1 t]	Water [1 kg]	Fine aggregate [1 t]	Steel [1 t]
GWP [kg CO_2eq.]	8.98E+2	5.70E-4	3.10E+0	7.67E+2
AP [kg SO_2 eq.]	1.48E+0	8.58E-7	4.33E-2	3.50E+0
EP [kg$(PO_4)^{3-}$ eq.]	2.11E-1	2.48E-7	3.67E-3	9.00E-1
ADPE [kg Sb eq.]	1.10E-3	2.44E-10	2.11E-7	4.20E-4
POCP [kg Ethene eq.]	1.42E-1	8.53E-8	6.64E-3	1.10E+0
ADPF [MJ]	3.44E+3	5.38E-3	3.99E+1	1.16E+4

2.4. Environmental impacts of recycled concrete aggregate

The environmental profile of recycled concrete aggregate is determined on the basis of how it is obtained. The source of environmental impact is primarily equipment used for the demolition of structures and machines used for the crushing of feed, sorting, screening, rinsing and removing impurities, as well as the transportation of aggregate to the concrete plant. For the purpose of this study, it was assumed that the demolition of the structure is performed using hydraulic hammers that constitute excavator equipment. The initial crushing of debris is performed on the construction site using a mobile jaw crusher. The obtained aggregate is then transported to the processing plant and re-crushed using an impact crusher. The loading of the feed into the crusher and the crushed aggregate onto the truck is performed using a wheel loader. It was assumed that the recovery potential of the aggregate is 60% [15] and that the remaining debris is disposed at a landfill site and is not used for construction purposes. Taking this assumption into account, an appropriately increased amount of demolished concrete with respect to the required aggregate content in the concrete mixture was adopted.

Table 3 summarises the characteristics of the construction equipment used in the RCA production process. It was assumed that the machines were equipped with diesel engines that met Tier 4 Final assumptions requiring the maintenance of a specific level of particulate matter and a significant reduction of nitrogen oxides (NOx) emissions relative to pre-existing regulations.

Table 3. The assumed characteristics of the equipment used in the production of recycled aggregates

Production stage	Demolition	Feed crushing	Aggregate loading	Aggregate re-crushing
type of equipment	hydraulic hammer	jaw crusher	wheel loader	impact crusher
power [KM/kW]	160/118	117/86	139/102	136/100
capacity [t/h]	45.5	80	330*	100
age [year]	6	6	6	6
type of propulsion	diesel	diesel	diesel	diesel

* While determining the capacity of the loader, it was assumed that the duration of the duty cycle including loading and discharge as well as manoeuvring with a full and empty bucket is 30 seconds and the bucket is filled to the maximum capacity.

Using the NONROAD model [6], which is a tool for estimating air pollution generated by construction equipment engines, the emission factors EF_{adj} of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO_2), sulphur dioxide (SO_2) and particulate matter (PM) for selected construction machines were determined. In the case of HC, CO and NOx emissions, the following relationship was used:

$$Ef_{adj}(\mathrm{HC,CO,NOx}) = Ef_{ss} \cdot TAF \cdot DF, \text{ g/hp-hr} \qquad (1)$$

where:

- A, b – constants for a given pollutant/technology type, for compression-ignition engines (Diesel) b = 1;
- A_{act} – machine annual activity, h;
- A_f – age factor, fraction of median life expended, $A_f = \frac{t_s \cdot i}{T_{\dot{z}}}$;
- DF – deterioration factor; $DF = 1 + A \cdot A_f^b$ for $A_f \leq 1$, for $DF = 1 + A$ for $A_f > 1$;
- EF_{ss} – zero-hour, steady-state emission factor, g/hp-hr;

TAF – transient adjustment factor; for Tier 4 Final: TAF = 1.0;
$T_ż$ – median life at full load, h;
a – equipment age, years;
i – load factor;
t_s – cumulative hours;
$t_s = A_{act} \cdot a$, h.

The data necessary for calculations is presented in Tables 4 and 5.

Tables 4–5. Data for calculating of factors for emissions generated during equipment operation, based on [6].

Type of equipment	$BSFC_{ss}$	EF_{ss}				A_{act}	$T_ż$	i
		HC	CO	NOx	PM			
hydraulic hammer	0.367	0.1314	0.087	0.276	0.0092	1092	4667	0.59
jaw crusher		0.1314	0.087	0.276	0.0092	955		0.43
wheel loader		0.1314	0.087	0.276	0.0092	761		0.59
impact crusher		0.1314	0.087	0.276	0.0092	955		0.43

Type of equipment	A			
	HC	CO	NOx	PM
hydraulic hammer	0.027	0.151	0.008	0.473
jaw crusher	0.027	0.151	0.008	0.473
wheel loader	0.027	0.151	0.008	0.473
impact crusher	0.027	0.151	0.008	0.473

A similar approach [6] was applied while determining the PM emissions:

$$EF_{\mathrm{adj}(PM)} = EF_{ss} \cdot TAF \cdot DF - S_{PM\mathrm{adj}},\ \mathrm{g/hp\text{-}hr} \tag{2}$$

taking into account the change in the sulphur content in the fuel by means of a correction factor :

$$S_{PM\mathrm{adj}} = \cdot\, 453.6 \cdot 7 \cdot soxcnv \cdot 0.01 \cdot (soxbas - soxdsl);\ \mathrm{g/hp\text{-}hr} \tag{3}$$

where:
$BSFC$ – in-use adjusted brake-specific fuel consumption (lb fuel/hp-hr);
$S_{PM\mathrm{adj}}$ – adjustment to PM emission factor to account for variations in fuel sulphur content, g/hp-hr;
soxbas – default certification fuel sulphur weight percent, *soxbas* = 0.33%;
soxcnv – grams PM sulphur/grams fuel sulphur consumed, *soxcnv* = 0.02247%;
soxdsl – episodic fuel sulphur weight percent (specified by user), *soxdsl* = 0.25%;
7.0 – grams PM sulphate/grams PM sulphur;

453.6 – conversion from lb to grams.

CO_2 and SO_2 emissions were determined on the basis of relationships:

$$CO_2 = (BSFC \cdot 453.6 - \mathrm{HC}) \cdot 0.87 \cdot 44/12;\ \mathrm{g/hp\text{-}hr} \tag{4}$$

$$SO_2 = (BSFC \cdot 453.6 \cdot (1 - soxcnv) - \mathrm{HC}) \cdot 0.01 \cdot soxdsl \cdot 2;\ \mathrm{g/hp\text{-}hr} \tag{5}$$

where:

0.01 – conversion from percent to fraction;
0.86 – carbon mass fraction of diesel;
2 – grams of SO_2 formed from a gram of sulphur;
44/12 – the ratio of CO_2 mass to carbon mass.

The output stream for the aggregate transport to the processing plant was determined on the basis of the Ecoinvent database, adopting a transport vehicle with a maximum payload of 17.3 t and assuming a transport distance of 25 km. The emissions were classified into relevant environmental impact categories and then subjected to a characterisation procedure that reflects the impact of each compound on environmental performance within the categories. The characterisation procedure consists of converting the emissions into the impact indicators of individual categories by multiplying the emissions volume with the corresponding characterisation factors (Table 6).

Table 6. Factors characterising the potential of given chemical compounds for environmental impact within categories

Compound [1 kg]	**Characterisation factors, c_f**			
	GWP [kg CO_2-eq.]	**AP [kg SO_2 eq.]**	**EP [kg$(PO_4)^{3-}$ eq.]**	**POCP [kg Ethene eq.]**
HC	28	–	0.075	0.11
CO	–	–	–	0.027
NOx	265	0.5	0.13	0.028
CO_2	1	–	–	–
SO_2	–	1.2	–	0.048

‘-’ – no factor for the compound

Hydrocarbons (HC) are a group of compounds, among which methane has a particularly significant influence on global warming [10, 11]. The impact of methane on the environmental effect within the global warming category is much greater than that of carbon dioxide; therefore, a factor corresponding to methane as the appropriate representative of the HC was used for characterisation. The NOx group includes nitrogen oxides and expresses the total emission of NO and NO_2. In the process of fuel combustion, it is mainly nitrogen oxide NO that is formed and as a result of its oxidation in the atmosphere, nitrogen dioxide NO_2 is formed. However, the research [7, 14] also indicates the presence of N_2O in the exhaust, which is a greenhouse gas and significantly affects the destruction of the ozone layer. Therefore, the influence of NOx on the environmental effect within the global warming category was assessed using a characterisation factor for N_2O, indicating an almost 300-times greater impact of this gas than carbon dioxide. It should be noted that for the assumed power and capacity of machines, these assumptions do not significantly affect the result of the analysis, but to a large extent, reflect the significance of methane and nitrous oxide with regard to the environment. The most significant factor is the impact of carbon dioxide and considering the available data, the analysis in this case can be limited only to carbon dioxide. For other categories, characterisation factors for HC and NOx groups were used. In the characterisation procedure, the CML environmental impact assessment method and the openLCA database were implemented.

Finally, the values of environmental impacts S_e (kg_{eqiv}/t) within the individual categories per unit of recycled concrete aggregate amount were determined based on the relationships:

$$EF_k = P \cdot \frac{EF_{adj} \cdot 0.7355}{c}; \text{ g/t} \tag{6}$$

$$S_e = \sum_{k=1}^{m} EF_k \cdot 0.001 \cdot cf_{ke}; \text{ kg}_{\text{equiv}}/\text{t} \tag{7}$$

where:

- C – machine's capacity, t/h;
- EF_k – emission factor of k[th] compound for 1 t of RCA, g/t;
- P – machine's power, kW;
- cf_{ke} – characterisation factor for k[th] compound within e[th] environmental impact category (Table 6);
- e – number of environmental impact category;
- m – number of considered compounds;
- 0.7355 – conversion from hp-hr to kWh.

The analysis considers no impact of recycled concrete aggregate production processes on the depletion of abiotic non-fossil resources (ADPE) under the assumption that they do not require exploitation of natural resources. A similar assumption was made in relation to transport using the tank-to-wheel model and considering only fuel consumption, not its supply chain [19]:

$$F_{ON} = BSFC \cdot (0.4536 / 0.7355) \cdot P \cdot i\,; \text{ kg/h} \tag{8}$$

where:

- F_{ON} – fuel consumption, kg/h;
- P – power of engine, kW;
- i – load factor;
- 0.4536 – conversion from lb to kg;
- 0.7355 – conversion from hp-hr to kWh.

The abiotic depletion potential for fossil resources F_{ADPF} was determined by converting the amount of fuel needed to operate the equipment to the amount of consumed energy using a characterisation factor cf_{ON} = 42 MJ/kg, expressing the calorific value for 1 kg of diesel oil:

$$F_{ADPF} = \frac{F_{ON} \cdot cf_{ON}}{C} \text{; MJ/t} \qquad (9)$$

The values of environmental impact within individual categories per unit of the concrete mixture components as well as of the reinforcing steel amounts are given in Table 2.

2.5. Environmental assessment

The result of the analysis conducted according to the presented procedure is the Ecopoint indicator E_p – a single value reflecting the environmental performance within all impact categories, calculated on the basis of the formula [2]:

$$E_p = \sum_{e=1}^{n} N_e \cdot w_e \qquad (10)$$

where:

- E_p – Ecopoints;
- N_e – normalised value of environmental impact within eth category, ;
- R_e – reference value for environmental impacts within eth category;
- S_{ej} – characteristic value of environmental impact within the eth impact category for jth material;
- cj – the amount of jth material;
- j – material (concrete mixture component or steel);
- e – environmental impact category;
- w_e – weight of eth environmental impact category.

The reference values and weights of environmental indicators were adopted in accordance with [3, 17] and summarised in Table 7.

Table 7. Reference values and weights of environmental indicators according to [3, 17]

	GWP	AP	EP	ADPE	POCP	ADPF
R_i	4.6E+12	2.36 E+10	9.70 E+10	3.23 E+7	1.58 E+10	3.32 E+13
w_i	1.16	1.18	1.14	1.00	1.27	1.00

3. Results and discussion

3.1. Summary of the results and general interpretation

The environmental assessment was conducted for three beams. This decision was taken for logistical reasons; the amount of aggregate needed to produce one beam is much smaller than the effective payload of the transport mean (14.7 t by the 0.85% utilisation rate), the incomplete load is uneconomical and may adversely affect the results of the environmental analysis. Using the NONROAD model, the emission factors EF_{adj} of HC, CO, NOx, PM, CO_2 and SO_2 were determined for the production processes of recycled concrete aggregate. Taking into account the characterisation factors (Table 6), on the basis of relationships (6, 7) the environmental impact of the unit of aggregate amount within individual environmental impact categories were determined. On the basis of the concrete mixture composition and data in Table 2, the environmental impacts of three beams for S1 and S2 scenarios were then calculated. The results are presented in one table (Table 8) with highlighting of the demolition process, which is not covered by the scenario S2 (Fig. 1).

Table 8. Characteristic values of the environmental impacts of materials for three reinforced concrete beams – scenarios S1 and S2 (in S2 scenario, the impacts resulting from the demolition process, included in the shaded column, are omitted)

	Cement	Water	Fine agg.	RCA					Steel
				Demolition	Feed crushing	Loading	Transport	Re-crushing	
GWP*	3.28E+3	1.16E+0	2.15E+1	4.65E+1	1.91E+1	3.32E+0	2.07E+1	1.06E+1	1.18E+3
AP	5.40E+0	1.74E-3	3.00E-1	8.51E-2	3.49E-2	6.08E-3	1.00E-1	1.95E-2	2.40E+0
EP	7.70E-1	5.04E-4	2.55E-2	3.50E-3	1.45E-3	2.50E-4	2.27E-2	8.07E-4	2.52E-1
ADPE	4.01E-3	4.96E-7	1.46E-6	0	0	0	0	0	1.94E-4
POCP	5.18E-1	1.73E-4	4.60E-2	4.93E-3	2.02E-3	3.51E-4	7.05E-3	1.13E-3	4.76E-1
ADPF	1.25E+4	1.09E+1	2.77E+2	3.16E+2	9.43E+1	2.26E+1	2.99E+2	5.27E+1	1.16E+4

*Indicator's units according to Table 2

Based on the results obtained for S1 and S2 scenarios, using the expression (10), the Ecopoint scores were calculated as the sum of the weighted, normalised environmental impacts of individual components. The Ecopoint indicator for the S1 scenario is Ep_{S1} = 2.5611E-9, and for the S2 scenario, Ep_{S2} = 2.5351E-9. Higher Ecopoint scores indicate higher environmental impacts; therefore, the S2 scenario is a more favourable variant from the environmental performance point of view. The difference between the Ecopoint indicators is insignificant and amounts to 1%, which reflects the minor influence of demolition on the total environmental impact generated in the production processes of all components of the concrete mixture and steel. Despite the fact that aggregate generally occupies 60% to 75% of the concrete volume (70% to 85% by mass) [1, 16] its environmental impact is dominated by the production processes of cement and, as in the present case, steel as well as other technological processes [13, 22] that require large amounts of energy and affect the depletion of abiotic resources.

3.2. S1 scenario analysis

Based on the performed calculations, the S1 scenario was analysed in terms of the influence of RCA on the total environmental impact resulting from the production processes of the concrete mixture components and reinforcing steel. Pie charts (3a and 3b) show the share of production processes of individual materials and the environmental impact categories respectively in total impacts expressed by the Ecopoint indicator.

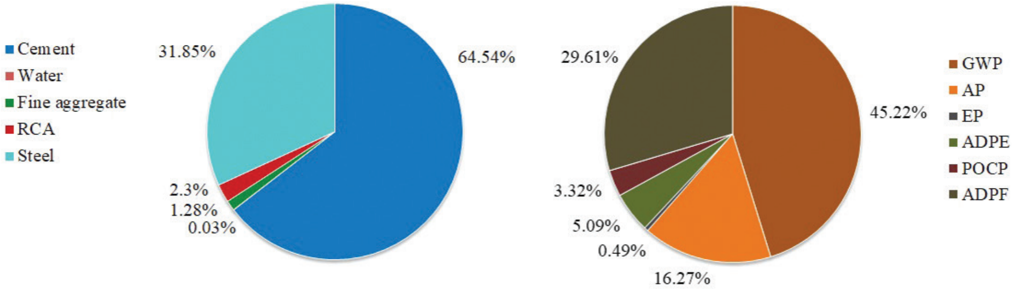


Fig. 3. Share of environmental impacts of individual materials production processes (3a) and categories (3b) in total impacts expressed by the Ecopoint indicator – S1 scenario

The greatest impact on the environmental performance of the product stage relates to cement (65%) and reinforcement (32%) production. This results from the energy intensity of clinker and steel production processes and the considerable amount of greenhouse gases, particularly CO_2, released into the atmosphere. The nature of the production processes simultaneously determines the significant contribution of global warming and abiotic depletion of fossil resources (3b) in the total environmental effect. The production of recycled concrete aggregate accounts for 2.3% of the total environmental impact. The results were obtained under the assumption that the equipment used for the production of recycled aggregates was produced in 2014 (Table 3). When considering the use of machines produced in 2011 and engines meeting Tier 3 requirements, the impact of recycled concrete aggregate increases to 3.3%.

The shares of the material production processes in environmental impacts within the individual categories for the S1 scenario are shown in the bar graph (Fig. 4). With regard to contributions to environmental impacts, cement clearly dominates and there is also a significant influence of reinforcing steel on the environmental performance within each category. Recycled concrete aggregate contributes the most to environmental impacts covered by the ADPF category (2.97%), which results from the energy-intensive processing of concrete debris.

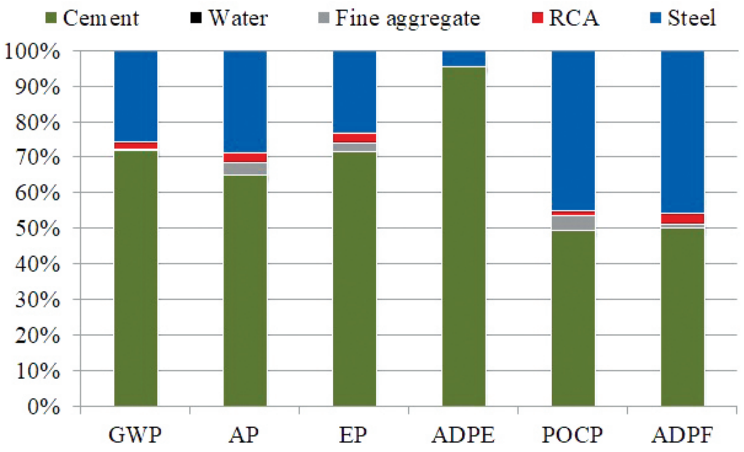


Fig. 4. Share of material production processes in the environmental impacts within individual categories – scenario S1

The results of the global analysis of the S2 scenario, in which the demolition process was omitted, do not differ significantly from the results of the S1 scenario analysis presented above. This is due to the minor contribution of demolition in the total impact generated by the components of the concrete mixture and steel (~1%). More pronounced differences between the S1 and S2 scenarios occur in the environmental analysis covering only the aggregate production processes presented in Section 3.3.

3.3. Detailed comparative analysis of the scenarios

Analysis of individual processes indicates that the largest share of the environmental impact resulting from the recycled concrete aggregate production, according to the S1 scenario, relates to the demolition process (44%) and then the processes of transport, crushing and loading (Fig. 5a). Thus, in order to comprehensively characterise the impact of recycled aggregate on the environment, consideration to the demolition process seems to be necessary and it is suggested to treat this process as a source of material for the production of aggregates. In the case of the S2 scenario (Fig. 5b), which excludes the demolition of the structure, the transport process of aggregates from the construction site to re-crushing in the processing plant becomes increasingly important (61%).

Figure 6 shows the influence of recycled concrete aggregate production processes on the total environmental impacts related to this production within individual categories. Aside from the significant influence of demolition in the S1 scenario (Fig. 6a), transport has a particular importance and the intensity of its impact depends on the transport distance. The environmental effect of recycled concrete aggregate production according to the S2 scenario (Fig. 6b) is determined by this factor. As a result of increasing the transport distance to 50 km or 100 km, the share of transport in the environmental effect of RCA increases to 51% and 67% in the S1 scenario and 76% and 86% in the S2 scenario, respectively. Therefore, further research is planned to determine the sensitivity of the analysis results to factors such as transport distance and equipment age. It should be noted that in the case of the large-scale production of concrete mixture and the related greater demand for aggregate, it is additionally required to take into account idle runs and emissions generated during transport.

Comparing the share of individual processes in the environmental impacts of RCA, it is stated that depending on the adopted scenario, optimisation will be targeted at the transport process (S2) or the demolition and transport processes (S1).

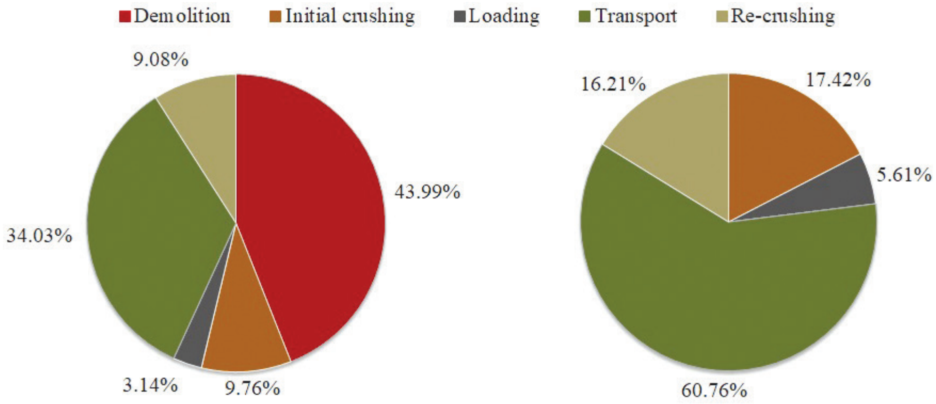


Fig. 5. Share of production processes in the total impact of recycled concrete aggregates: (5a) scenario S1, (5b) scenario S2

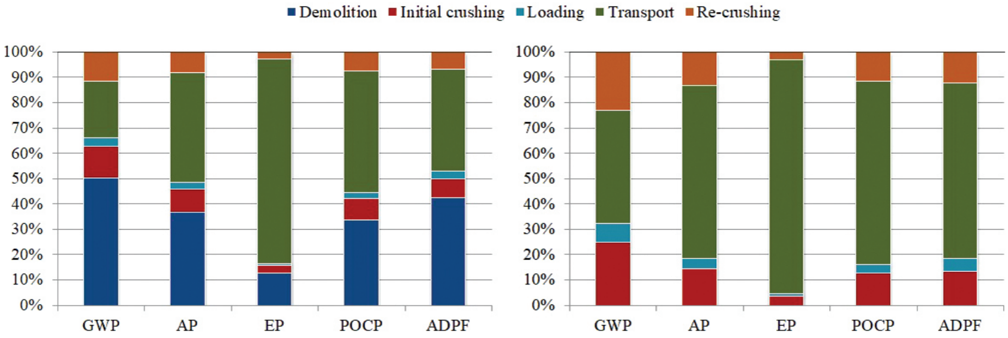


Fig. 6. The influence of aggregate production processes on environmental impacts within individual categories: (6a) S1 scenario, (6b) S2 scenario

The influence of recycled aggregates on ozone layer depletion requires additional analysis. Previous research [18] suggests that there are no significant changes to the results obtained; however, it do not provide exhaustive data on the aggregate production processes included in the analyses. Therefore, assuming that the recycled aggregate has a negligible influence on environmental impacts in this category could be over-simplifying the issue. The creation of the hole in the ozone layer is a consequence of the release of gases (including nitrogen oxides generated during fuel combustion) into the atmosphere, and for this reason, with an adequate quality of data, it should be included in the analysis.

4. Conclusions

In the conducted research, two scenarios of recycled concrete aggregate production (S1, S2) were compared in terms of the impact of production processes, including the demolition process, on the total environmental impacts of reinforced concrete beams and the aggregate itself. Based on the results, it was found that:

- The demolition process accounted for just over 1% of the total environmental impact; with such a minor contribution, omitting the demolition in the analysis of the first stage of the life cycle (product stage) is not significantly imprecise.
- More pronounced differences between S1 and S2 scenarios occurred in the environmental analysis covering only the aggregate production processes.
- In the case of the S1 scenario, demolition is responsible for almost half of the environmental impacts generated during production.
- The exclusion of demolition (scenario S2) caused a significant increase in the contribution of transport in the environmental effect of recycled concrete aggregates (from 34% to 61%).
- Recycled concrete aggregate contributed the most to environmental impacts covered by the ADPF category (almost 3% of total category impact).
- Environmental impacts resulting from the aggregate production depended on the characteristics of the machine park, engine parameters and transport distance.
- Although the S1 scenario had higher Ecopoint scores, it is recommended for the comprehensive assessment of the influence of recycled concrete aggregate on the environmental effect.

References

[1] ACI Committee *Aggregates for Concrete*, ACI Education Bulletin E1-07, 2007.
[2] Building Research Establishment (BRE), [online] http://www.bre.co.uk (access: 02.2019).
[3] Castellani V., Benini L., Sala S., Pant R., *A distance-to-target weighting method for Europe 2020*, The International Journal of Life Cycle Assessment 21/2016, 1159–1169.
[4] EN 1992-1-1:2004 Eurocode 2: Design of concrete structures, Part 1–1: General rules and rules for buildings, 2004.
[5] EN 15643-2 Sustainability of construction works – assessment of buildings, part 2: framework for the assessment of the environmental performance, 2011.
[6] EPA Exhaust and crankcase emission factors for nonroad engine modeling – Compression-ignition, 2010.
[7] EPA Nitrogen Oxides (NOx), why and how they are controlled EPA-456/F-99-006R, 1999.
[8] Estanqueiro B.A.M, *Life cycle assessment of the use of recycled aggregates in the production of concrete*, Instituto Superior Técnico, Universidade Técnica de Lisboa-UTL, Lisboa 2011.

[9] Estevez B., Aguado A., Josa A., *Deconstruction and Materials Reuse CIB Publication 287,* Proceedings of the 11th Rinker International Conference, 2003.

[10] IIASA The Greenhouse Gas Methane (CH4): Sources and Sinks, the Impact of Population Growth, Possible Interventions. WP-92-042, 1992.

[11] Kirkinen J., Palosuo T., Holmgren K., Savolainen I., *Greenhouse Impact Due to the Use of Combustible Fuels: Life Cycle Viewpoint and Relative Radiative Forcing Commitment,* Environmental Management 42/2008, 458–469.

[12] Koper A., Koper W., *Projektowanie betonów konstrukcyjnych na kruszywach z recyklingu,* Materiały Budowlane 3/2017, 38–41.

[13] Marinković S., Radonjanin V., Malešev M., Ignjatović I., *Comparative environmental assessment of natural and recycled aggregate concrete,* Waste Management 30/2010, 2255–2264.

[14] Mollenhauer K., Tschoke H., *Handbook of diesel engines,* Springer, Berlin 2010.

[15] Nagataki S., Gokce A., Saeki T., Hisada M., *Assessment of recycling process induced damage sensitivity of recycled concrete* aggregates, Cement and Concrete Research 34/2004, 965–971.

[16] Okonkwo V.O., Arinze Emmanuel E., *A Study of the Effect of Aggregate Proportioning On Concrete Properties,* American Journal of Engineering Research 7/2018, 61–67.

[17] Sala S., Crenna E., Secchi M., Pant R., *Global normalisation factors for the Environmental Footprint and Life Cycle Assessment,* JRC Technical Reports, 2017.

[18] Serres N., Braymand A., Feugeas F., *Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment,* Journal of Building Engineering 5/2016, 24–33.

[19] Silva C.M., Gonçalves G.A., Farias T.L., Mendes-Lopes J.M.C., *A tank-to-wheel analysis tool for energy and emissions studies in road vehicles,* Science of The Total Environment 367/2006, 441–447.

[20] Tošić N., Marinković S., Dašić T., Stanić M., *Multicriteria optimization of natural and recycled aggregate concrete for structural use,* Journal of Cleaner Production 87/2015, 766–776.

[21] UEPG (European Aggregates Association), [online] http://www.uepg.eu (access: 01.2019).

[22] Wałach D., Dybeł P., Sagan J., Gicala M., *Environmental performance of ordinary and new generation concrete structures – a comparative analysis,* Environmental Science and Pollution Research 26/2019, 2980–3990.

If you want to quote this article, its proper bibliographic entry is as follow: Gicala M., Halicka A., *The influence of the demolition process on the environmental impact of reinforced concrete structures based on recycled aggregate,* Technical Transactions, Vol. 9/2019, pp. 81–96.

TECHNICAL TRANSACTIONS 9/2019
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.19.099.10881
SUBMISSION OF THE FINAL VERSION: 26/08/2019

Monika Matuszkiewicz orcid.org/ 0000-0002-7479-4013
m.mat@wilsig.tu.koszalin.pl
Faculty of Civil Engineering, Environmental and Geodetic Science, Koszalin University of Technology

Analysis of guyed lattice masts considering various types of mast shaft geometrical imperfections

Analiza masztów o kratowych trzonach z różnymi imperfekcjami geometrycznymi

Abstract
The paper covers an analysis of guyed masts as per the second order theory. The influence of various types of mast shaft imperfections was analysed based on the example of a certain 200 m-high lattice guyed mast structure with 3 guy levels. The computations were performed taking into account the mast shaft with sway imperfections, imperfections associated with an offset of structure nodes and bow imperfections. As there are no guidelines concerning imperfections in the current European Standard EN 1993-3-1, the permissible assembly deviation values were taken as the reference point. Based on the obtained results of the analysis some final conclusions and comments have been formulated that may be useful in the design of mast structures.

Keywords: guyed masts, sway imperfections, bow imperfections, carrying capacity condition utilisation

Streszczenie
Praca dotyczy analizy masztów z odciągami w ujęciu teorii II rzędu. Na przykładzie pewnej konstrukcji kratowego masztu wysokości 200 m z 3. poziomami odciągów badano wpływ różnych form imperfekcji trzonu masztu na obliczenia statyczno-wytrzymałościowe masztu. W obliczeniach uwzględniono trzon masztu z imperfekcjami przechyłowymi, imperfekcjami związanymi z wzajemnym przesunięciem węzłów konstrukcji oraz imperfekcjami łukowymi. Z braku wytycznych normowych w aktualnej europejskiej normie EN 1993-3-1odnośnie do imperfekcji za punkt odniesienia przyjęto wartości imperfekcji równe dopuszczalnym odchyłkom montażowym. Na podstawie uzyskanych wyników analizy sformułowano pewne wnioski końcowe i uwagi, które mogą być przydatne w projektowaniu konstrukcji masztów.

Słowa kluczowe: maszty z odciągami, imperfekcje przechyłowe, imperfekcje łukowe, wytężenie

1. Introduction

In accordance with current standard guidelines [5], guyed masts using elastic global analysis as per second order theory should be computed. The internal forces in the structure elements must, therefore, be related to the final, deformed configuration of the structure. Perfect mast structures are idealised. In real member structures there are always some imperfections. The most frequently occurring imperfections in steel member structures include transverse and eccentric loads, initial bar curvature and various structural defects, eg. own stresses [12]. In structures with imperfections, according to the load increase, displacements increase in a strictly defined way, dictated by imperfective factors. Therefore, it is important to adopt proper imperfection form. Unfortunately, in the current standard regulations there are no guidelines pertaining to the form of adoption of the initial imperfections and their magnitude in guyed mast computations. There is also no information that such imperfections can be omitted from computations. The community of scientists and designers interpret this lack of guidelines pertaining to imperfections differently. According to some people, keeping the tolerances recommended in Annex F to the standard [5] fully justifies the analysis of the mast shaft with ideal geometry. According to others, the lattice mast shaft should be treated as a uniform built-up column, for which, as per [4], bow imperfections between the fixing levels featuring the maximum amplitude value equal to $L/500$ (L – span length of mast shaft). Assumption of the mast shaft imperfections as for a uniform build-up column appears, in the author's opinion, to be a simplification. Bow imperfections with maximum amplitude $L/500$ pertain to a member with hinged ends because this assumption corresponds to its buckling form. In guyed masts, due to the geometric non-linearity of the guys, the stiffness values of elastic supports in guy fixing points are characterised by wide variation and depend on the current mast configuration. These supports differ, therefore, from typical steel structure supports, and so the buckling form of the mast shaft is also different than in typical steel structures [8].

In this study, based on the example of a specific mast structure, a comparative analysis of the "perfect" type mast shaft and the "imperfect" type mast shaft was performed. However, due to the lack of standard guidelines, the permissible assembly deviations values, specified in Annex F of the standard [5], were taken as the reference point. The most important of the listed assembly tolerances include:

A) The final position of the centre line along the entire mast height should fall within a vertical cone with the radius of $H/1,500$ at the top of mast (H – mast height);
B) After erection, the tolerance on the alignment of 3 consecutive guy connections on the shaft is limited to $(L_1 + L_2)/2,000$ (L_1, L_2 – lengths of the two consecutive spans of the shaft)(according to [2] – deviation from the vertical of any two structure points should not exceed 0.05%);
C) Maximum initial deflection of the mast shaft between two guy levels should be $L/1,000$ (L – distance between the guy levels).

The main objectives of the analysis are an attempt to address the question of which imperfections affect the increase of the internal forces in the mast elements and how the consideration of imperfections affects the effort of the mast shaft member and the effort of the guys.

2. Mast structure description

The subject of the analysis is a 200 m high lattice guyed mast (Fig. 1). The mast shaft was designed as S355 steel in form of trihedral space truss with side width a = 2.5 m. As legs, member Ø 168.3/14.2 mm pipes were used, and as mast face lacing – pipes Ø 76.1/4 mm (bolted connections between bracing members and leg members). The mast guys were fixed at heights of 65.0 m, 125.0 m and 175.0 m. For the guys, spiral strand steel ropes 1 x 61, Ø 32 mm, rope grade R_r = 1,570 MPa and a minimum breaking force of 823.0 kN were used. The assumed modulus of elasticity of ropes E was equal to 160 GPa. The assumed values of initial guy forces at all guy levels are the same and amount to 75 kN (according to [5] – they do not exceed 10% of the rope breaking force).

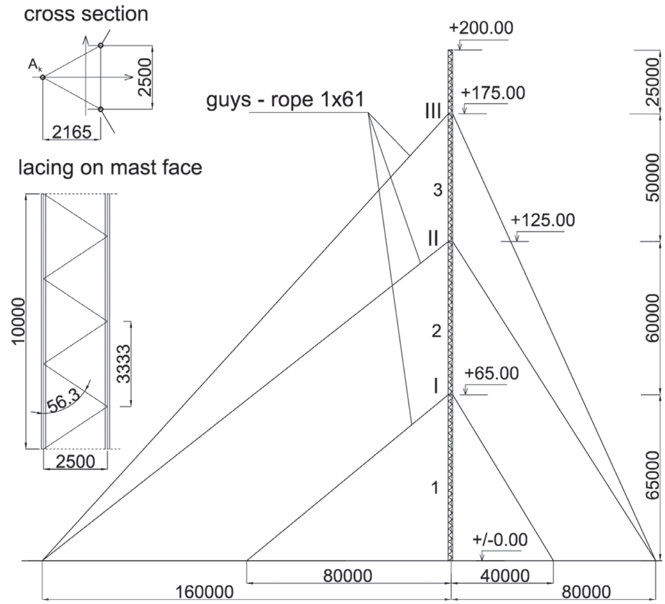


Fig. 1. Mast structure diagram

3. Actions and analysis area

The assumption was made that the mast would be located in the 2nd wind load zone for the territory of Poland as per [3], in the second category arena. The value of the base wind pressure for this zone is 420 Pa. The mast structure has been qualified to the second reliability class for which the partial factors for permanent loads are equal to 1.1 and for variable loads 1.4. Schemes of the mast wind load were determined in accordance with [5] (Fig. 2).

The wind load acting on mast structure consists of the mean load acting on the entire height of the structure and a number of the patch loads acting only on some fragments of the structure. The structure's own weight (excluding its outfit) and wind loading for the two most unfavourable directions of wind action $W1$ and $W2$ were considered in the analysis (Fig. 2).

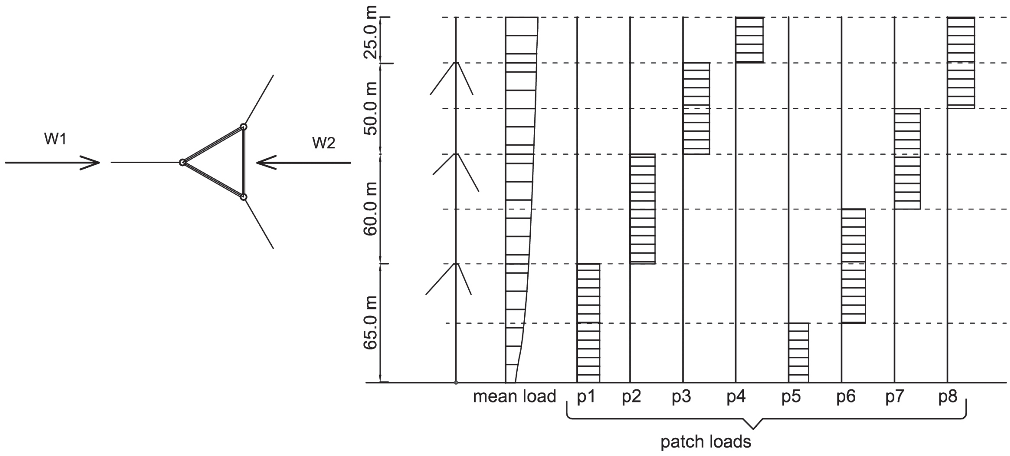


Fig. 2. Wind load diagrams and wind directions

The computations were performed for the "perfect" type mast shaft and the structure with imperfections whose forms and values were taken into account based on the assembly tolerance values described in Annex F of the standard [5]:

A) The maximum deflection from vertical of the mast shaft top by the value $R = H/1{,}500 = 133$ mm (Fig. 3);
B) After erection the tolerance on the alignment of 3 consecutive guy connections on the shaft should not exceed the value $(L_1 + L_2)/2{,}000 = (65{,}000 + 60{,}000)/2{,}000 = 62.5$ mm value, and according to [2], deviation from the vertical of any two structure points should not exceed 0.05%, i.e., at the first level of guy connections, the deviation of the mast shaft from the vertical the value of $65{,}000 \cdot 0.05\% = 32.5$ mm, at the second level $60{,}000 \cdot 0.05\% = 30$ mm, and at the third level $50{,}000 \cdot 0.05\% = 65$ mm (Fig. 4);
C) Maximum initial deflection of the mast shaft between two guy levels should not exceed $L/1{,}000$. The proper form of bow imperfections in the analysed guyed mast example was adopted in accordance with the determined first buckling form of the mast shaft with the assumption of the maximum buckling value equal to $L/1{,}000 = 65{,}000/1{,}000 = 65$ mm (Fig. 5) [7, 8]. The values of displacements of the other nodes were determined proportionally, in accordance with the displacement eigenvector coordinates based on the mast shaft stability analysis.

The static computations from the second order theory perspective, with consideration of the non-linearity of the guys, were performed using the *Mast1* software described in [11]. Finally, mast computations for 126 various load combinations were conducted. The values of the internal forces of the mast structure elements – both for the perfect structure and the imperfect structure – were computed, in accordance with [5], as the total load effect:

$$S_{TM} = S_M \pm S_P \tag{1}$$

where:

S_M – the mean wind load effect,
S_P – the total patch load effect.

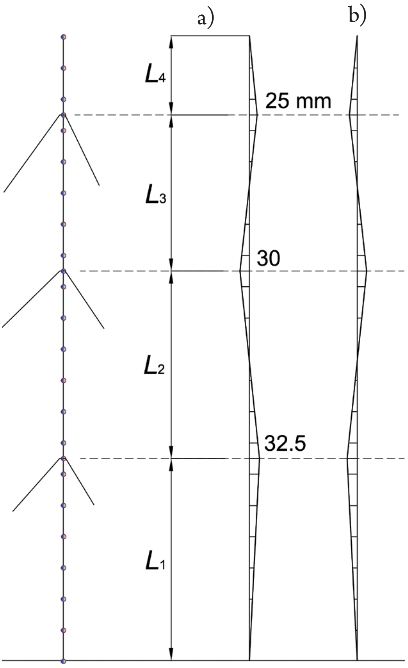


Fig. 3. Adopted mast shaft imperfections – type A): a) in one direction, b) in the opposite direction

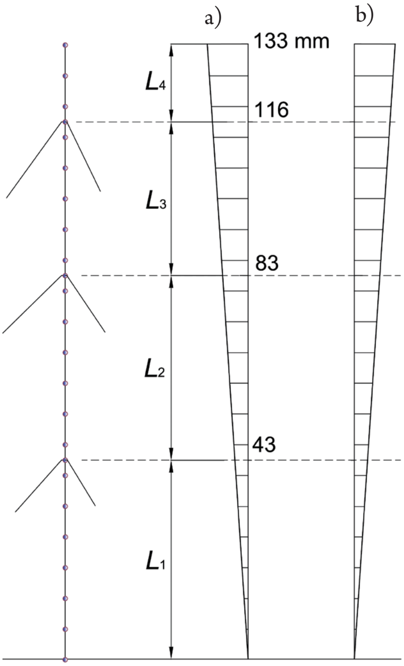


Fig. 4. Adopted mast shaft imperfections – type B): a) in one direction, b) in the opposite direction

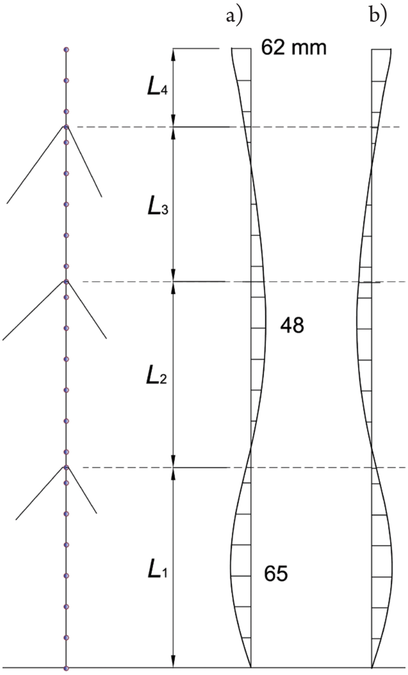


Fig. 5. Adopted mast shaft imperfections – type C): a) in one direction, b) in the opposite direction

The total patch load effect, S_p, is calculated from the formula:

$$S_p = \sqrt{\sum_{i=1}^{N} S_{PLi}^{\ 2}}\,, \tag{2}$$

in which S_{PLi} – the effect of i-th wind patch load, N – the total number of patch load schemes required in the calculations.

Due to the fact that the values of the internal forces of the mast elements don't depend directly on the load acting on the mast, but are the result of laborious calculations, the substitute model of the mast shaft (beam-column model) can be successfully used in the analysis. The authors of papers [9, 10, 12, 13] have shown a good convergence of mast structure computations with the assumption of the beam-column model and the frame-truss mast shaft model with a continuous members of legs, modelled as 3-D beam elements and hinged connected to the legs with bracing members, modelled as 3-D truss elements.

4. The analysis results

Selected results of the static-strength computations of mast structures elements are presented in tabular form. Since the computations were made taking the substitute beam--column model of the mast shaft, the normal forces in the leg elements have been determined as $N_{Ed} = N_1 + N_2$, where $N_1 = N/3$ and $N_2 = M/h$ (in the case of a positive value of bending moment) or $N_2 = M/2h$ (in case of a negative value of bending moment), N, M – design values of normal forces and bending moments in the mast shaft members, h – the height of the triangular section of the mast shaft ($h = a\sqrt{3}/2$, a – axial spacing between legs members).

The maximum value of the shear force for the perfect type mast shaft structures was V_{Ed} = 49.3 kN. The value increased by less than 6% only in the case of including the bow imperfections in computations, as shown in Fig. 5. In other cases of imperfections, the differences didn't exceed 1%.

Table 1. The maximum values of normal forces in the leg member of the mast shaft N_{Ed} [kN] ($W1$, $W2$ – wind direction; a), b) – according to Figures 3, 4, 5)

Location	Perfect type of structure	Imperfections A	Imperfections B	Imperfections C
Level 0	–379.4 ($W1$)	–379.5 ($W1$a)	–379.4 ($W1$a)	–379.4 ($W1$a)
Span 1	–605.7 ($W1$)	–606.1 ($W1$b)	–608.5 ($W1$a)	**–634.9** ($W1$b)
Support I	–507.6 ($W2$)	–508.2 ($W2$a)	–513.1 ($W2$a)	–509.0 ($W2$a)
Span 2	–442.5 ($W1$)	–442.9 ($W1$b)	–445.1 ($W1$b)	–455.6 ($W1$a)

Support II	–498.6 (*W*2)	–498.9 (*W*2a)	–504.8 (*W*2b)	–507.5 (*W*2a)
Span 3	–391.9 (*W*2)	–392.1 (*W*2b)	–396.1 (*W*2b)	–397.1 (*W*2a)
Support III	–356.4 (*W*2)	–356.5 (*W*2a)	–334.5 (*W*2b)	–357.7 (*W*2a)
Cantilever	–383.8 (*W*2)	–384.1 (*W*2a)	–384.2 (*W*2a)	–384.4 (*W*2a)

According to [5], in the computations as per the second order theory, checking the mast shaft strength comes down to checking the load capacity condition for a single leg member taking into account its buckling between the bracing member nodes:

$$N_{Ed} / N_{b,Rd} \le 1. \qquad (3)$$

The design buckling resistance of the compression leg member shall be defined from the formula:

$$N_{b,Rd} = \chi \cdot A_1 \cdot f_y / \gamma_{M1}, \qquad (4)$$

where:

A_1 = 68.7 cm^2 – leg member cross-section area,
χ = 0.798 – reduction factor corresponding with the leg member buckling length L_1 = 333 cm,
γ_{M1} = 1.0 as per the Polish National Annex, therefore $N_{b,Rd}$ = 1,945.0 kN.

Percentage utilisation of the end condition of the analysed mast in spans and on supports – the guy fixing points, are presented in Table 2.

The computed maximum values of the mast guys at particular levels and the percentage ultimate limit state utilisation of the guys are presented in table 3.

As the reader can see, consideration in the computations of the sway imperfections (Fig. 3) and imperfections associated with an offset of structures nodes (Fig. 4) has practically no effect on the change of internal forces in the mast structure elements. In the case of computations of the mast with bow imperfections (Fig. 5) the increase of the leg member effort applies only to the first span and amounts to approx. 2%, due to the increase of the computed bending moments in the span by almost 12%.

Table 2. Percentage of leg member carrying capacity condition utilisation

Location	**Perfect type of structure**	**Imper-fections A**	**Imper-fections B**	**Imper-fections C**
Level 0	20	20	20	20
Span 1	31	31	31	**33**
Support I	26	26	26	26

Span 2	23	23	23	23
Support II	26	26	26	26
Span 3	20	20	20	20
Support III	18	18	17	18
Cantilever	20	20	20	20

Table 3. The maximum force values in the guys F_{Ed} [kN] and the percentage ultimate limit state utilisation

Guy level	Perfect type of structure		Imperfections A		Imperfections B		Imperfections C	
	F_{Ed}	F_{Ed}/F_{Rd}	F_{Ed}	F_{Ed}/F_{Rd}	F_{Ed}	F_{Ed}/F_{Rd}	F_{Ed}	F_{Ed}/F_{Rd}
I	181.5	33	181.6	33	182.3	33	182.9	33
II	180.5	33	180.7	33	181.0	33	181.6	33
III	219.8	40	220.1	40	220.0	40	220.2	40

5. Final conclusions

The influence of various types of mast shaft imperfections on the values of internal forces and the effort of mast structure elements has been analysed in the paper on the example of a particular guyed mast structure. Due to the lack of any standard guidelines as to the form of imperfections and their values, the mast shaft has been analysed subjected to sway imperfections, with the maximum value on the top of the mast equal to $H/1{,}500$, imperfections associated with non-axial positioning of the mast structure nodes, shifted against each other by the maximum $(L_1 + L_2)/2{,}000$, and bow imperfections, with maximum amplitude $L/1{,}000$. In the latter case, the appropriate curvilinear mast shaft shape was found based on the stability analysis of the mast shaft in the prestress condition and supported at the guy fixing points, where the stiffness of the elastic supports based on the values of initial guy forces have been determined. In the guyed mast analysed, as in the case of the mast structures described in [8], the zero-value points of horizontal displacements are located beyond the guy fixing points (Fig. 5). It has been shown that the sway imperfections and imperfections associated with an offset of structure nodes have practically no effect on values of internal forces and the effort of the mast structure elements. A slight influence on the increase of the span bending moments was noted only in the case of bow imperfections which had an effect on a slight increase of the effort of the mast shaft legs. Similar results were observed by the author in the case of analysis of other mast structures, characterised by a greater mast shaft slenderness [6, 7]. The increase of the effort of the mast span legs in any cases did not exceed 10%.

The relatively small differences observed in the results of computations of the mast structure with bow imperfections compared with computations of the "perfect" mast structure, originate from the specific properties of mast structures characterised by large (even several metre) nodal displacements of the mast shaft caused by external loads. The situation is quite different in typical steel structures where nodal displacements caused by load are of the same order as the assumed initial imperfection values.

Due to the extremely laborious computations of mast structures considering mast shaft geometrical imperfections and the very slight effects of these imperfections, one could, in the author's view, omit the imperfections in the analysis, and with a careful approach, in calculating the design buckling resistance of the compression leg members of the mast, in view of model uncertainty, reduce the buckling resistance by 10%, which will result in the design of mast structures with an appropriate level of safety.

References

[1] Ben Kahla N., *Equivalent beam-column analysis of guyed towers*, Computers and Structures, 55/1995, 631–645.

[2] EN 1090-2: 2008 + A1: 2011: Execution of steel structures and aluminium structures. Part 2: Technical requirements for steel structures.

[3] EN 1991-1-4: 2005. Eurocode 1: Actions on structures. Part 1-4: General actions – Wind actions.

[4] EN 1993-1-1: 2006. Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for building.

[5] EN 1993-3-1: 2006. Eurocode 3: Design of steel structures. Part 3-1: Towers, masts and chimneys – Towers and masts.

[6] Matuszkiewicz M., *Imperfections in calculations of guyed lattice masts*, Archives of Civil Engineering, LX, 4/2014, 409–420.

[7] Matuszkiewicz M., *Influence of the initial guy forces on the static computations of mast taking into account the mast shaft buckling form*, Recent Progress in Steel and Composite Structures, Giżejowski et al., Taylor&Francis, 2016, 571–575.

[8] Matuszkiewicz M., *Wybrane zagadnienia analizy masztów z odciągami*, Wydawnictwo Uczelniane Politechniki Koszalińskiej, Koszalin 2017.

[9] Matuszkiewicz M., Orzłowska R., *Wpływ sił drugiego rzędu w trzonie masztu na obliczenia masztów z odciągami*, Inżynieria i Budownictwo, 6/2017, 329–332.

[10] Paez P.M., Sensale B., *Analysis of guyed mast by the stability function based on the Timoshenko beam-column*, Engineering Structures, 152/2017, 597–606.

[11] Pałkowski S., *Konstrukcje cięgnowe*, WNT, Warszawa 1994.

[12] Pałkowski S., *Podstawy stateczności stalowych konstrukcji prętowych*, Wydawnictwo Uczelniane Politechniki Koszalińskiej, Koszalin 2016.

[13] Wahba Y.M.F., Madugula M.K.S., Monforton G.R., *Evaluation of non-linear analysis of guyed antenna towers*, Computers and Structures, 68/1998, 207–212.

TECHNICAL TRANSACTIONS 9/2019
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.19.100.10882
SUBMISSION OF THE FINAL VERSION: 21/08/2019

Natalia Paszek orcid.org/0000-0001-7017-6026
natalia.paszek@polsl.pl
Marcin Górski orcid.org/0000-0001-7028-924X
Faculty of Civil Engineering, Silesian University of Technology

The basic mechanical properties of the fluidised bed combustion fly ash-based geopolymer

Podstawowe cechy mechaniczne geopolimeru na bazie fluidalnego popiołu lotnego

Abstract

The main goal of the research was to check the influence of different factors on the mechanical behaviour of the fluidised bed combustion (FBC) fly ash-based geopolymer. Tests have shown that the increasing the proportion of sodium silicate to sodium hydroxide causes a decrease of compressive strength and an increase of flexural strength. The addition of aggregate significantly increased flexural strength but decreases compressive strength. Samples cured at higher temperatures obtained higher strength. Finally, it was concluded that taking into account the mechanical behaviour, FBC fly ash-based geopolymer can be treated as an alternative building material; however, its strength is lower than a metakaolin-based geopolymer made of the same mixture composition.

Keywords: FBC fly ash, geopolymer, curing conditions, compressive strength, flexural strength

Streszczenie

Głównym celem badania było wyznaczenie wpływu wybranych czynników na wytrzymałość geopolimeru bazującego na fluidalnym popiele lotnym. Badanie wykazało, że wzrost stosunku masowego szkła wodnego do wodorotlenku sodu powoduje spadek wytrzymałości na ściskanie i wzrost wytrzymałości na rozciąganie geopolimeru. Dodatek kruszywa (piasku) powoduje natomiast wzrost wytrzymałości na rozciąganie i spadek wytrzymałości na ściskanie. Odnotowano, że próbki dojrzewające w wyższych temperaturach uzyskują wyższą wytrzymałość. Na podstawie wykonanych badań stwierdzono, że biorąc pod uwagę wytrzymałość badanego geopolimeru, można uważać go za alternatywny materiał budowlany. Wytrzymałość badanego geopolimeru jest jednak niższa od wytrzymałości geopolimeru na bazie metakaolinu.

Słowa kluczowe: popiół fluidalny, geopolimer, warunki dojrzewania, wytrzymałość na rozciąganie i na ściskanie

1. Introduction

Fluidised-bed combustion (FBC) fly ash is a by-product of the combustion process in a fluidised-bed boiler furnace. Fluidised-bed combustion occurs at relatively low temperatures (around 800–900°C). For this reason, obtained fly ash has a low glassy phase and consists mainly of irregular dehydrated grains and dehydroxylated gangue minerals of significant pozzolanic activity [3, 11]. The characteristics of FBC fly ash differ from the characteristics of fly ash from conventional combustion process. As a result of its properties, the possibility of using FBC fly ashes as an addition to concrete is limited [2]. In Poland, FBC fly ashes are used mainly for the stabilisation of soils, in mining technologies, for geotechnical filling during earthworks, as an addition in the ceramic industry and sometimes in building binders [11]. Since fluidised-bed combustion is becoming more popular nowadays, scientists are trying to find new uses for FBC fly ash. For example, Brzozowski [2] presents research on the application of FBC fly ash in underwater concrete. He reports that it is possible to use FBC fly ash in underwater concrete; however, both compressive and tensile strength decreases with the increase of the FBC fly ash content. He places particular emphasis on the problem of the workability of the concrete mixture with the addition of FBC fly ash. The number of works devoted to FBC fly ash-based geopolymer is small, but this subject has been raised in the past. Chindaprasirt et al. [3] presents tests performed on aFBC fly ash-based geopolymer. Tests showed that there is the possibility to make a durable FBC fly ash-based geopolymer; however, the compressive strength can be significantly enhanced (from 10 MPa to around 25 MPa) through the addition of pulverised coal combustion high calcium fly ash.

The main goal of works presented in this paper was to examine the possibility of using particular FBC fly ash coming from the Polish company TAURON Polska Energia S.A. The authors also wanted to check the influence of different factors on the geopolymer's strength.

1.1. The influence of the activator ratio on geopolymers strength

Experiments concerning the issue of the influence of the ratio of sodium silicate to sodium hydroxide on geopolymers strength give diverse results. Hardjito et al. [7] claims that the increase of sodium silicate to the sodium hydroxide mass ratio causes significant growth of the compressive strength of a fly ash-based geopolymer. Similarly, research shown in [9] proves that the strength of *a* metakaolin-based geopolymer increases with the increase of sodium silicate to the NaOH molar ratio. Heah et al. [8] did not notice any direct dependence between the ratio of sodium silicate to NaOH and the compressive strength of a kaolin-based geopolymer after seven days, but reports the general increase of strength with the increase of the above-mentioned ratio after one-hundred-eighty days. Poowancum et al. [10] came to different conclusions. According to [10], the strength of a clay-based geopolymer decreases rapidly with the increase of the volume ratio of sodium silicate to sodium hydroxide from 0.5 to 1.0. It is also reported that strength increases for the ratio of 1.5. On the contrary, Fernandez-Jimenez [6] reports that the compressive strength of *a* fly ash-based geopolymer decreases constantly with the increase of the sodium silicate content in the mixture.

1.2. The influence of the curing conditions on the strength of geopolymers

Many scientific papers are concerned with the influence of curing conditions, especially the influence of curing temperature on the mechanical behaviour of different kinds of geopolymer. Bing-hui et al. [1] found that compressive strength tested after seven days increases monotonically with the increase of the curing temperature of metakaolin-based geopolymer samples. However, the growth of the strength was registered only to a temperature of 60°C; for higher curing temperatures, a significant decrease in strength was noticed. Ekaputri et al. [4] came to different conclusions. Scientists did not notice any significant difference after seven days in either the flexural or the compressive strength of metakaolin-based geopolymer samples cured at different temperatures. No significant influence of curing temperature on geopolymer density was noticed during this experiment. But it was registered that after fourteen days, the compressive strength of samples cured at higher temperatures is greater. The decrease of density of a metakaolin-based geopolymer with the increase of the curing temperature was described in [12]. According to [12], both the flexural and compressive strength of a geopolymer after one day increases with the increase of the curing temperature but with time, the strength of samples cured at lower temperatures (20°C and 40°C) is higher than the strength of samples cured at 60°C or 80°C. Swanepoel et al. [13] identified a decrease in the density of a fly ash-based geopolymer with increases to the curing temperature. In their paper, it can be found that after seven and twenty-eight days, the strength of samples cured at 40°C and 50°C is higher than the strength of samples cured at 60°C or 70°C. By contrast, Hardjito et al. [7] describe the almost monotonic growth of the strength of a fly ash-based geopolymer with the increase of the curing temperature. Zhang et al. [14] performed testing on a red mud-fly ash-based geopolymer and came to the conclusions that both short- and long-term strength is higher for samples cured at higher temperatures.

As can be concluded, both the influence of the curing conditions and the ratio of sodium silicate to sodium hydroxide on geopolymers strength depends not only on the type of precursor but also on the specific mixture composition and can differ even within one general type of geopolymer. This, as well as the fact that there are not many reports from experiments performed on the fluidised bed combustion ashes, are the main reasons why authors decided to check the influence of curing conditions and the ratio of sodium silicate to NaOH on the strength of the geopolymer made of the new mixture.

2. Laboratory tests

The main goal of the laboratory tests was to establish the flexural and compressive strength and the density of FBC fly ash-based geopolymer samples. In the first part of testing, the influence of the ratio of sodium silicate to sodium hydroxide on the strength of the FBC fly ash-based geopolymer was investigated. In the second part of testing, the strength of FBC fly ash-based geopolymer samples containing different amounts of aggregate (sand) was compared with the strength of metakaolin-based geopolymer samples. In the last part of the experiment, the influence of the curing temperature on the strength of geopolymer samples made from one chosen mixture was investigated. A flexural strength test was performed on prismatic samples with dimensions of 40x40x160 mm. Broken halves of the samples were subjected to compressive strength testing in accordance with standard EN 196-1:2016 [5].

2.1. Mixtures compositions

Several different mixtures containing different amounts of FBC fly ash, sand, sodium silicate and sodium hydroxide were prepared. Three control mixtures containing metakaolin instead of FBC fly ash were also prepared. The water solution of sodium hydroxide was prepared a minimum twenty-four hours before the mixture preparation. In all mixtures, the concentration of sodium hydroxide was equal to 10 mol/L. The used sodium silicate solution had a ratio of SiO_2 to Na_2O of between 2.4 and 2.6. The minimum content of oxides (SiO_2 and Na_2O) in the sodium hydroxide solution was 39%. The particle size distribution of sand used as an aggregate is presented in Fig. 1.

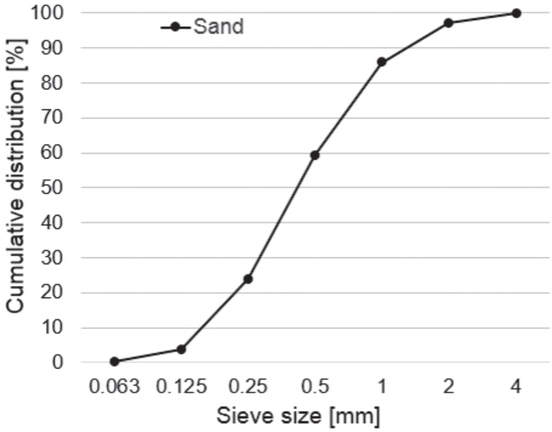


Fig. 1. Particle size distribution of the sand

The compositions of all mixtures are presented in Table 1. Mixtures are identified with codes which represent the main characteristics of their composition. In the first four geopolymer mixtures, either FBC fly ash (FA) or metakaolin (M) were used as the precursors. Numbers 2, 2.5 and 3 represent the ratio of sodium silicate to sodium hydroxide. The next four mixtures (5, 6, 7 and 8) contain the precursor (FA – fly ash or M – metakaolin) and aggregate (sand). The numbers following the letters in the name of the mixtures represent the percentage mass ratio of the precursor to the aggregate. There is a small difference in the amount of activator added to the mixtures containing metakaolin and the FBC fly ash.

Table 1. Composition of geopolymer mixtures

No	Mixture	FBC Fly ash		Metakaolin		Sand		Sodium silicate		NaOH	
		[kg/m³]	[%]	[kg/m³]	[%]	[kg/m³]	[%]	[kg/m³]	[%]	[kg/m³]	[%]
1	**FA 2**	1083	51.7	–	–	–	–	674	32.2	337	16.1
2	**FA 2.5**	1083	51.7	–	–	–	–	723	34.5	289	13.8
3	**FA 3**	1083	51.7	–	–	–	–	762	36.3	253	12.0
4	**M 2**	–	–	1083	51.7	–	–	674	32.2	337	16.1
5	**FA 33/67**	657	24.9	–	–	1335	50.6	430	16.3	215	8.1
6	**FA 50/50**	898	33.7	–	–	898	33.7	581	21.8	285	10.7
7	**M 33/67**	–	–	657	25.9	1335	52.6	365	14.4	182	7.2
8	**M 50/50**	–	–	898	36.4	898	36.4	449	18.2	225	9.1

The difference is caused by the greater water absorption of the FBC fly ash. The FBC fly ash-based geopolymer mixtures need more liquid to obtain proper workability.

2.2. Preparation of the samples

All samples were prepared in the same manner. In the case of samples containing the precursor and aggregate, these two dry components were first mixed together. The activators were then mixed together for 5 minutes. The activators were then poured into the vessel with the dry components and all ingredients were mixed together. At the end of the process, the mixture was placed in the moulds and covered. All mixtures were cured for the first twenty-four hours in the climatic chamber at a temperature of 60°C and humidity 40%. After this time, the samples were demoulded and cured at room temperature and with a humidity level of around 25–30% in the laboratory for the remaining six days. Strength tests were conducted seven days after the samples were prepared.

In addition to the above, mixture no 3 FA 3 was chosen for the determination of the influence of curing temperature on the strength and density of the FBC fly ash-based geopolymer. The next three batches of this mixture were prepared. One batch was cured for the first 24 hours in the climatic chamber at a temperature of 40°C and a humidity of 40%. After this time, the samples were demoulded and cured at room temperature for the next six days. Two other batches were cured for the whole seven days at room temperature. One of these was demoulded after twenty-four hours and the second was demoulded after seven days (immediately prior to the strength test).

2.3. The tests results

The test results are presented in bar graphs. The bars represent the average value of flexural and compressive strength. The numbers written above the bars are the exact value of the average strength. On each bar, there are shown the minimum and maximum strength values obtained in each set of samples in the form of small black line segments. The upper line segment is the maximum and the lower line segment is the minimum value of strength.

In addition to the flexural and compressive strengths, the densities of samples were also measured. Each sample was weighed before the strength test. The mass of each sample was divided by its volume to obtain the density. The tables presented below present the average value of densities of samples from each set.

2.3.1. The influence of sodium silicate to sodium hydroxide ratio

Figure 2 presents the results of flexural and compressive strength tests performed on FBC fly ash-based geopolymer samples activated with the addition of different proportions of activators.

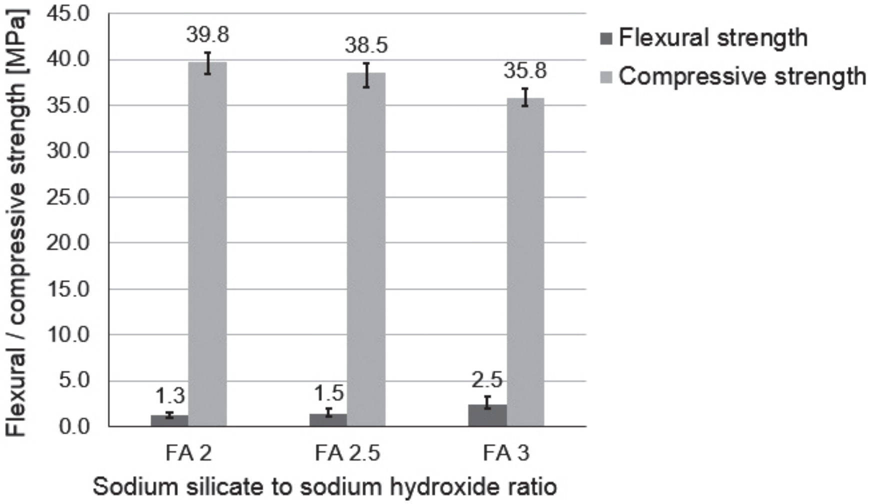


Fig. 2. Flexural and compressive strength of geopolymer samples containing different sodium silicate to sodium hydroxide ratios, after 7 days

As shown in the graph, flexural strength slightly increases with increases in the ratio of sodium silicate to sodium hydroxide while the compressive strength decreases.

Table 2 presents the average densities of FBC fly ash-based geopolymer samples made from mixtures containing different ratios of sodium silicate to sodium hydroxide. No strict dependence between activator ratio and density was observed. The differences in densities between geopolymers made of different mixtures are small.

Table 2. Density of geopolymer made of different mixtures

	FA 2	FA 2.5	FA 3
Density [kg/m³]	1570	1520	1530

2.3.2. The comparison of strength of FBC fly ash-based geopolymer with metakaolin-based geopolymer

Figures 3 and 4 present a comparison of the flexural and compressive strength test results obtained from FBC fly ash-based geopolymer samples with results obtained from metakaolin-based geopolymer samples. The graphs show results of samples containing 33, 50 and 100% of precursor (FBC fly ash or metakaolin). The abbreviation P/A refers to precursor/aggregate. The numbers following the letters represent the percentage mass ratio of the precursor to the aggregate. All of the compared samples contain sodium silicate to sodium hydroxide at the ratio 2.0.

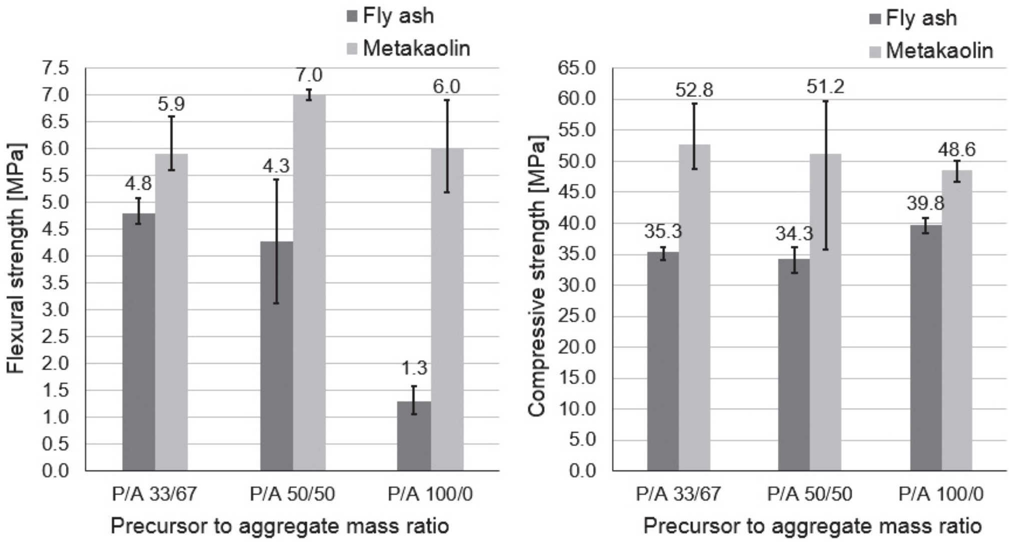


Fig. 3. Flexural and compressive strength of geopolymer samples based on different precursors and having different precursor to aggregate ratios; after 7 days

Figure 3 shows that the FBC fly ash-based geopolymers have lower flexural strength than the metakaolin-based geopolymers. The biggest difference is between the samples containing only the precursor without any aggregate. The metakaolin-based geopolymer without aggregate addition has over 4.5 times the flexural strength of the fly-ash based geopolymer. According to the diagram, the flexural strength of the FBC fly ash-based geopolymers decreases with the decrease of the aggregate content. In the case of the metakaolin-based geopolymers, there is no monotonic dependence between the aggregate content and flexural strength.

The compressive strength of the FBC fly ash-based geopolymers is lower than that of the metakaolin-based geopolymers. There is no clear dependence between the aggregate content and the compressive strength in either the case of the FBC fly ash-based geopolymers or in the case of the metakaolin-based geopolymers. Contrary to the results of flexural strength, the FBC fly ash-based samples containing only the precursor obtained the highest compressive strength. The standard deviation of the compressive strength results obtained by the FBC fly ash-based geopolymer was much smaller than that of the metakaolin-based geopolymer.

Table 3 presents the average densities of FBC fly ash-based and metakaolin-based geopolymer samples containing different amounts of aggregate. The density of the FBC fly ash-based geopolymer is smaller than that of the metakaolin-based geopolymer. In both cases, the density increases with the increase of the aggregate (sand) content.

Table 3. The density of samples made with different ratios of precursor to aggregate (P/A)

Density [kg/m^3]		**P/A 33/67**	**P/A 50/50**	**P/A 100/0**
	FBC fly ash	1850	1780	1570
	metakaolin	2080	1950	1590

2.3.3. The influence of curing temperature on FBC fly ash-based geopolymer strength

During this part of the experiment, it was observed that samples cured for the whole time at room temperature and demoulded after twenty-four hours got cracked. The system of cracks appeared on the upper surface of samples and in the upper parts of the side surface (see Fig. 4). Furthermore, these samples were affected by apparent shrinkage. After seven days, the samples lost around 3 mm of length and 1 mm of width. The cracks and shrinkage were probably caused by the fact that samples were demoulded and as a consequence, all the surfaces were exposed to air before the reactions inside the geopolymer's structure were finished. The strength of cracked samples was not included in the graphs. No apparent shrinkage nor cracks were registered in the case of other samples. For comparison, Fig. 5 presents uncracked surfaces of samples cured for the first twenty-four hours at elevated temperatures of 40°C and 60°C.

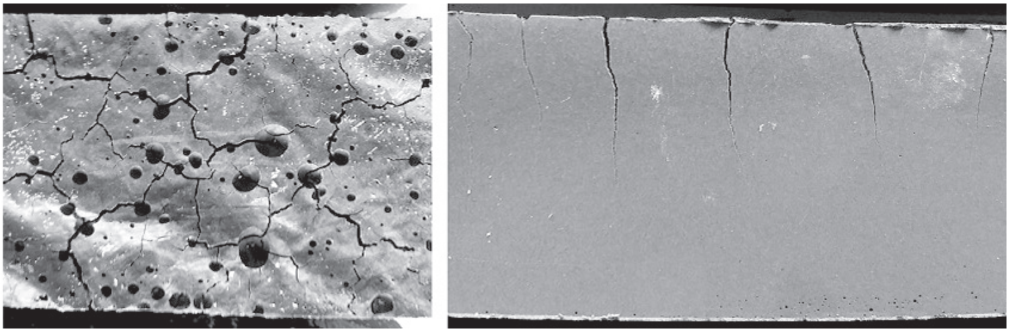


Fig. 4. Cracked upper and side surfaces of the sample cured at 20°C and demoulded after 24 hours

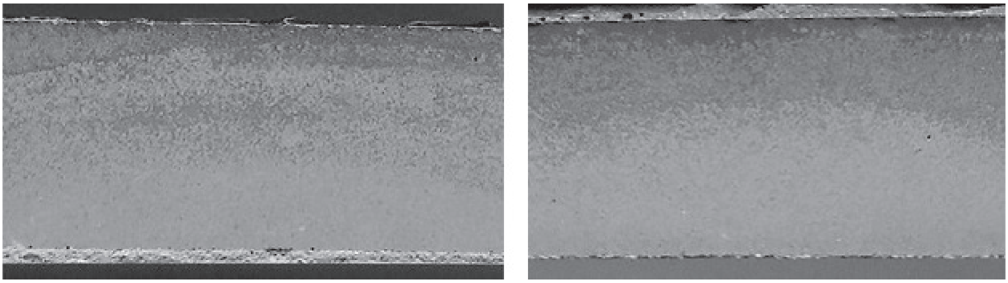


Fig. 5. Uncracked surface of the sample cured at 40°C and 60°C for the first 24 hours

Figure 6 presents the results of flexural and compressive strength tests performed on FBC fly ash-based geopolymer samples cured under different conditions. The curing conditions are described on the X-axis. Samples cured at room temperature for the entire time and demoulded after seven days (immediately prior to the test) are marked as 20°C. Samples cured for the first twenty-four hours at temperatures of 40°C and 60°C are marked accordingly. These two groups of samples were demoulded after twenty-four hours and cured at room temperature for the rest of the time. This test was conducted on samples made of the mixture named as FA 3.

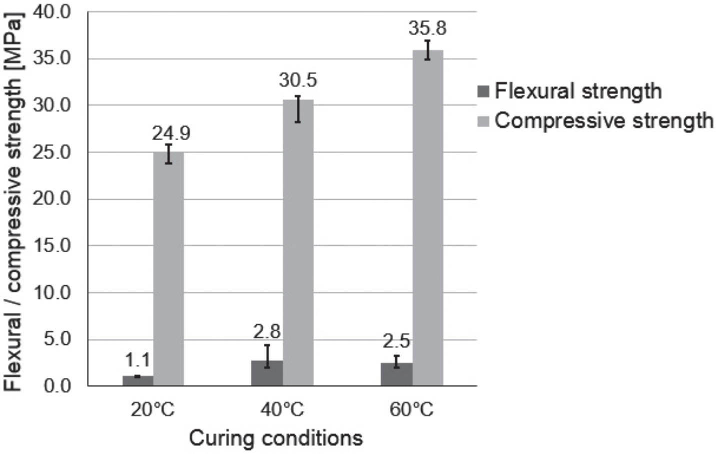


Fig. 6. Flexural and compressive strength of geopolymer samples after 7 days and cured in different conditions

The graph shows that compressive strength increases with the increase of the curing temperature. The growth of compressive strength is almost monotonic. In the case of flexural strength, it can be seen that the strength of samples cured in the climatic chamber at increased temperature for the first 24 hours is higher than of samples cured all the time at room temperature. However, the flexural strength of samples cured at 40°C is slightly higher than the strength of samples cured at 60°C. The test has also shown that FBC fly ash-based geopolymers should not be demoulded after 24 hours while cured at room temperature because cracks and significant shrinkage are unwanted and dangerous features.

Table 4 presents the average densities of the FBC fly ash-based geopolymer cured under different conditions. It was noticed that density decreases with the increase of the curing temperature; however, the difference between the density of the samples cured at 40°C and at 60°C is small. The higher density of samples cured at room temperature is probably caused by a greater amount of unevaporated water inside the structure. However, it could also be caused by differences in the structure formed during the curing process.

Table 4. Density of the geopolymer cured under different conditions

	20°C	40°C	60°C
Density [kg/m^3]	1750	1580	1530

3. Summary

The above paper presents tests performed on the fluidised bed combustion fly ash-based geopolymer. The main goal of the tests was to verify the influence of different factors on the mechanical behaviour of the FBC fly ash-based geopolymer and to assess whether it is possible to treat it as a building material.

Three different ratios of sodium silicate to sodium hydroxide were used in the mixtures: 2.0, 2.5 and 3.0. It was observed that compressive strength decreases and flexural strength increases slightly with the increases to the ratio of sodium silicate to sodium hydroxide. No influence of the activator ratio on the density of the geopolymer was observed.

The influence of the curing temperature on mechanical behaviour was checked on one chosen mixture. Two batches were cured for the whole duration at room temperature and two were cured at higher temperature (40°C and 60°C) for the first twenty-four hours. The experiment showed that the compressive strength increases slightly while the density decreases with the increase of the curing temperature. It was also registered that geopolymer samples cured at room temperature and demoulded after twenty-four hours are cracked while the surface of samples demoulded after seven days is plain.

Two mixtures were prepared with the addition of aggregate (sand) to the precursor at different mass proportions. The strength results were compared with results obtained from metakaolin-based geopolymer samples of almost the same composition. It occurred that the addition of sand significantly increases flexural strength but decreases compressive strength. All FBC fly ash-based samples achieved lower strength results than metakaolin-based samples. In the case of both precursors, the addition of sand increases the density of the samples.

The highest compressive strength (39.5 MPa) was obtained by samples containing the precursor and activators mixed at a ratio of 2 and cured at 60°C. The highest flexural strength (4.8 MPa) was obtained by samples containing 33% of precursor and 67% of aggregate with activators mixed at a ratio of 2 and cured at 60°C.

To sum up, taking into account the mechanical behaviour of FBC fly ash-based geopolymer, this material can be treated as an alternative building material.

The research is funded by BKM-547/RB6/2018. Materials were provided by TAURON Polska Energia S.A.

References

[1] Bing-hui M., Zhu H., Xue-min C., Yan H., Si-yu G., *Effect of curing temperature on geopolymerization of metakaolin-based geopolymers*, Applied Clay Science 99/2014, 144–148.

[2] Brzozowski P., *Możliwości wykorzystania popiołów lotnych ze spalania w kotłach fluidalnych do betonów układanych pod wodą*, Civil and Environmental Engineering/Budownictwo i Inżynieria Środowiska 2/2011, 5–11.

[3] Chindaprasirt P., Jenjirapanya S, Rattanasak U., *Characterizations of FBC/PCC fly ash geopolymeric composites*, Construction and Building Materials 66/2014, 72–78.

[4] Ekaputri J.J., Junaedi S., Wijaya, *Effect of curing temperature and fiber on metakaolin-based geopolymer*, Procedia Engineering 171/2017, 572–583.

[5] EN 196-1 :2016, Method of testing cement – Part 1: Determination of strength, Brussels 2016.

[6] Fernandez-Jimenez A., Palomo A., *Factors Affecting Early Compressive Strength of Alkali Activated fly ash (AAFA) Concrete*, Materiales de Construccion 57(287)/2007, 7–22.

[7] Hardjito D, Rangan B.V., *Development and properties of low-calcium fly ash-based geopolymer concrete*, Research Report GC 1, Faculty of Engineering, Curtin University of Technology, Pert, Australia 2005.

[8] Heah C.Y., Kamarudin H., Mustafa Al Bakri A.M., Bnhussain M., Luqman M., Nizar I.K., Ruzaidi C.M., Liew Y.M., *Study on solids-to-liquid and alkaline activator ratios on kaolin-based geopolymers*, Construction and Building Materials 35/2012, 912–922.

[9] Pelisser F., Guerrino E.L., Menger M., Michel M.D., Labrincha J.A., *Micromechanical characterization of metakaolin-based geopolymers*, Construction and Building Materials 49/2013, 547–553.

[10] Poowancum A., Horpibulsuk S., *Development of Low Cost Geopolymer from Calcined Sedimentary Clay*. RILEM Bookseries 10/2015, 359–364.

[11] Rajczyk K., *Popioły lotne z kotłów fluidalnych i możliwości ich uszlachetniania*, Wydawnictwo Instytut Śląski, Opole 2012.

[12] Rovnanik P., *Effect of curing temperature on the development of hard structure of metakaolin--based geopolymer*, Constraction and Building Materials 24/2010, 1176–1183.

[13] Swanepoel J.C., Strydom C.A., *Utilisation of fly ash in a geopolymeric material*, Applied Geochemistry 17/2002, 1143–1148.

[14] Zhang M., Zhao M., Zhang G., Sietins J.M., Granados-Focil S., Pepi M.S., Xu Y., Tao M., *Reaction kinetics of red mud-fly ash based geopolymers: Effects of curing temperature on chemical bonding, porosity, and mechanical strength*, Cement and Concrete Composites 93/2018, 175–185.

If you want to quote this article, its proper bibliographic entry is as follow: Paszek N., Górski M., *The basic mechanical properties of the fluidised bed combustion fly ash-based geopolymer*, Technical Transactions, Vol. 9/2019, pp. 107–118.

TECHNICAL TRANSACTIONS 9/2019
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.19.101.10883
SUBMISSION OF THE FINAL VERSION: 1/08/2019

Michał Piątkowski orcid.org/0000-0002-4803-7561
michal.piatkowski@tu.koszalin.pl
Environmental and Geodetic Sciences, Faculty of Civil Engineering, Koszalin University of Technology

The influence of the geometry of imperfect trusses on the loading of transversal roof bracings

Wpływ geometrii kratownicy z imperfekcjami na obciążenie poprzecznego tężnika dachowego

Abstract

Geometrical imperfections of compressed chords in truss girders generate loads on the transverse roof bracings which are connected to the truss girders. The real distribution of this load is contrary to the model presented in the EN 1993-1-1 standard. The influence of the shape of the truss girder with geometrical imperfections on the load of transverse roof bracing has been numerically analysed in this article. The most commonly used shapes of truss girders as well as selected geometrical parameters have been considered. The obtained research results were used to determine the load acting on roof purlins and bracing rods in a typical hall structure.

Keywords: geometry of truss, bracing, geometrical imperfections

Streszczenie

Imperfekcje geometryczne pasów ściskanych w dźwigarach kratowych wywołują obciążenie połączonych z nimi poprzecznych tężników połaciowych. Rzeczywisty rozkład takiego obciążenia jest sprzeczny z modelem przedstawionym w normie EN 1993-1-1. W artykule przeprowadzono analizę numeryczną wpływu kształtu dźwigara kratowego z imperfekcjami geometrycznymi na obciążenie poprzecznego tężnika połaciowego. Uwzględniono stosowane najczęściej kształty dźwigarów oraz wybrane parametry geometryczne. Uzyskane wyniki wykorzystano do określenia obciążenia działającego na płatwie oraz pręty stężeń typowej konstrukcji hali.

Słowa kluczowe: geometria kratownicy, stężenie, imperfekcje geometryczne

1. Introduction

In order to design hall structures in which steel trusses act as truss girders, the proper design of transverse and longitudinal roof bracings is crucial. Transverse roof bracings play a vital role as they stabilise the upper chords of trusses against out-of-plane buckling by reducing the chords' buckling lengths. In the case of roofs without purlins, bracing can be replaced by structural trapezium-shaped sheets from roof envelopes. Both the transverse roof bracing and the trapezium-shaped sheet can transmit environmental loads such as wind pressure on front walls or technological loads, for example, forces caused by the acceleration or deceleration of cranes. For this reason, both the transverse roof bracing and the trapezium-shaped sheet should have appropriate levels of stiffness in order to prove effective in the structure [1, 5]. While designing these elements, loads generated by the truss girder resulting from geometrical imperfections of the truss girder should also be taken into consideration. This imperfection, in the form of curvature of the compressed chord, generates a horizontal load which can be represented as nodal loads in the case of roof bracing and, in the case of the trapezium-shaped sheet, as a distributed load.

The load of roof bracing resulting from the imperfection of the truss girder's compression chord can be determined using the guidelines set in accordance with the EN 1993-1-1 standard which assumes a parabolic shape of the imperfection. This load is related both to the maximum compression force of chord N_{Ed} and the value of imperfection e_0 equal to $L/500$ (L – length of the compression chord). The number of braced girders m is taken into account by coefficient α_m and the stiffness of the roof bracing is taken into account by additional deformation δ_d which is calculated iteratively. The load of roof bracing thus determined is uniformly distributed because the equations indicated in the standard [7] are based on the analogy of horizontal thrust in a parabolic arch under a uniformly distributed load. In addition, this load should be self-balanced and should consider elastic deformation of the roof bracing δ_d resulting from load q and other loads (e.g. wind pressure on front wall) which are presented in Fig. 1.

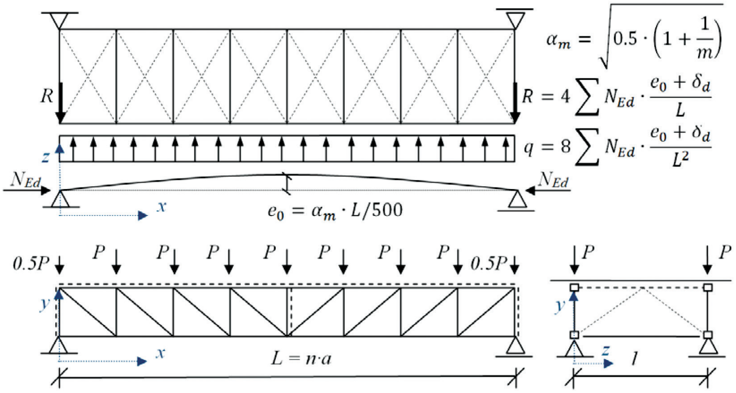


Fig. 1. Standard-indicated notional load of transverse roof bracing originating from a girder with imperfections

Recent theoretical analyses [3, 6] and experimental research [8] reveal that the standard modelling of the bracing load resulting from the imperfection of truss girders does not correspond to reality due to numerous simplifications of the standard model, which are described in detail in previous papers [3, 6]. The author's theoretical models, which are recommended in the papers, demonstrate that the actual load of roof bracing $q(x)$ is non--uniform and sign-changing within the distance of around $L/4$ from the supports in the case of a single-span truss. Additionally, it has been proven that the values of nodal load generated by the trusses on roof bracing may be much higher than the values of the analysis performed in accordance with EC3 (Fig. 2). The recommended models make it possible to calculate the value of the nodal load on roof bracing in a simple way while considering the following factors:

- various deformations of compressed chord, e.g. sinusoidal, parabolic or complex;
- any distributions of longitudinal force in the chord;
- simultaneous initial imperfection of the bottom chord;
- sway imperfection of the whole truss.

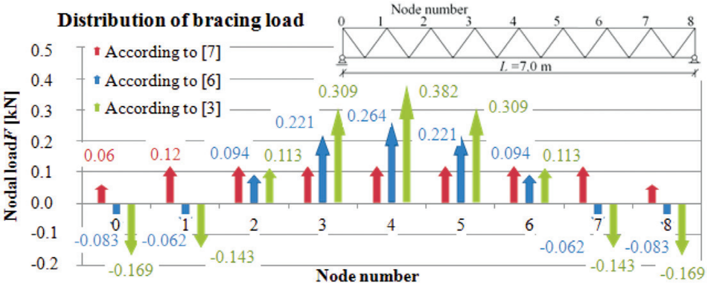


Fig. 2. Standard and theoretical load of bracing

The experimental research which is presented in paper [8] confirmed the non-uniform and sign-changing distribution of the bracing load resulting from the imperfection of truss. Tests on seven meter long models of truss with parallel chords and V-type web members are described in the paper. As an out-of-plane imperfection, the sinusoidal shape of a compressed chord was adopted. In the experimental research, the imperfection value of $e_0 = L/175 = 40$ mm was adopted. An example of nodal load distribution of roof bracing resulting from research model [8] and calculated according to the empirical guidelines [6] is presented in Fig. 2.

At the testing stage, horizontal reactions of transverse supports fixed to selected nodes of chords were measured. The obtained results were confirmed by the relevant numerical analysis (Fig. 3).

Certain quantitative differences between empirical (Fig. 2) and experimental (Fig. 3) values result from the elastic deformation of the bottom chord, which has been indicated in paper [4].

Commonly used in hall structures, truss girders are characterised by diverse geometry depending on the intended use of the hall structure, the type of roof cladding system or architectural factors. These geometries can evidently have a quantitative influence on the distribution of the roof bracing load as the imperfection value e_0 is based on the length of chord L. In the case of a truss with arched and pitched chords, this length depends on the inclination of the roof and the arch height. Therefore, it may be different in the case of trusses with the same support spacing but with different geometry. An additional factor possibly influencing the nodal load of an imperfect truss on roof bracing is truss height due to the influence of the inclination of webs; this was proven in papers [3] and [6].

The indicated relationships were derived empirically and confirmed experimentally only in the case of a truss with parallel chords. It is therefore justified to conduct relevant numerical parametric analyses which consider different geometries of truss girders applied in practice.

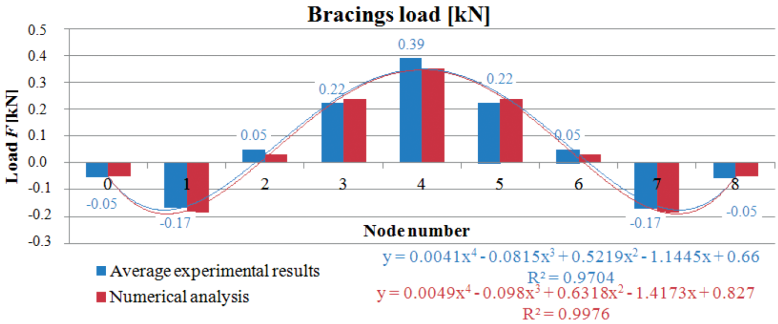


Fig. 3. Experimental results [6]

2. Numerical model and analysis

Parametric analyses were conducted using single-span steel trusses with a length between supports of L = 24.0 m (not in the case of truss purlin – G10*). The numerical analysis of the influence of the static scheme is presented in paper [2]. In this analysis, three variable parameters were considered:

- geometric shape of truss;
- height of the truss with parallel chords;
- inclination of roof or height of arch (in the case of arched truss girders).

An example of truss geometry and the numbering of the upper chord nodes are presented in Fig. 4.

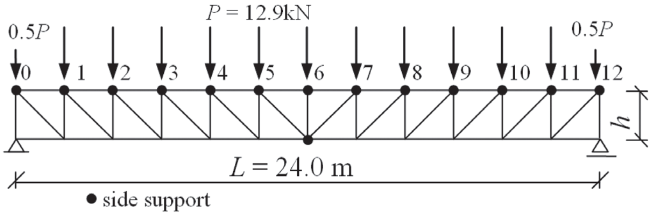


Fig. 4. Dimensions of the truss and numbering of the nodes of the upper chord

Only the gravitational load of P = 12.9 kN, which was applied to the nodes of the upper chord, and typical N-type web members were considered in the parametric analysis. This load, as well as the geometry shown in Fig. 4, were used to determine the probable cross sections of particular truss elements. Having completed a static analysis and design procedure in accordance with [7], chords with a HEB 140 cross section and web members with a SH 100 x 6 cross section were adopted.

The examined truss girders are presented in Fig. 5. The value of h = 2.0 m was adopted as the basic truss height. In the case of trusses with a lowered bottom chord, axial height from the lowered chord to the fulcrum was adopted as height h. This height was graded for G1-G7 geometries every 0.5 m from the basic value h = 2.0 m to the value h = 4.0 m. With regard to pitched trusses, G2-G5 and G8 geometries, the inclination angles of upper chords from 3° to 15° were considered. In the case of arched truss girders, G6, G7 and G9 geometries, heights of arched chord from f = 0 to $f = L/7.5$ were considered.

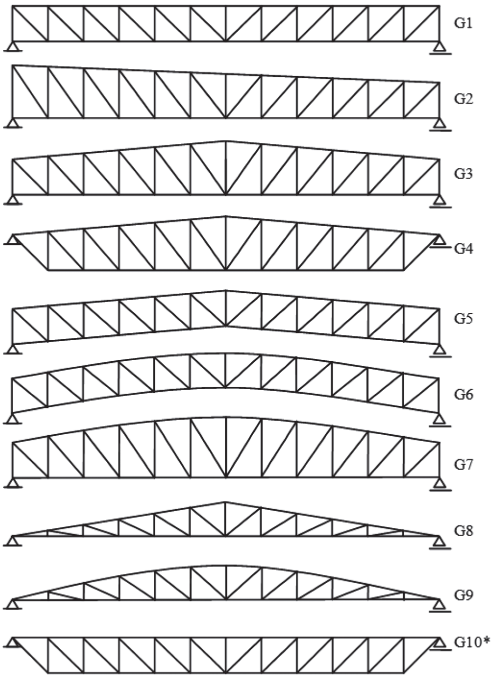


Fig. 5. Geometry of examined truss girders

In each case, transverse roof bracing was modelled as a rigid support system due to displacement in the direction transverse to the plane of truss. These supports were located in each node of the upper chord and in the mid-span of the bottom chord (Fig. 4).

In the case of G1-G7 geometries, the value h = 2.0 m was used as the basic height of truss. In the case of G2-G5 and G8 geometries, the value of 3° was used as the basic inclination of the upper chord. For G6, G7 and G9 geometries, the value $f = L/40$ was used as the basic arch height of the upper chord.

G10* geometry corresponds to the typical structural solutions of truss purlins. In typical structures, truss purlins attain a span length of around 12.0–18.0 m. For the purposes of parametric analysis in the case of G10* geometry, the length L = 12.0 m, the height h = 0.5 m and the gravitational load P = 2.15 kN were adopted.

Parametric analyses were conducted by means of the SOFiSTiK program [9] using its text module for parametric description of the analysed trusses. A geometrically and materially non-linear analysis with geometric imperfections was performed. A bi-linear elasto-plastic model of material with parameters corresponding to S235 steel was considered. The analysed trusses were modelled using beam-type finite elements with six degrees of freedom at each node. The distance between the truss joints was divided into twenty finite elements. A sinusoidal shape of imperfection in the upper chord was adopted. Its value e_0 was $L/500$ (L – length of compressed chord). Geometric imperfection was modelled directly by changing the coordinates of all finite element nodes of the upper chord. Rigid connections between webs and chords were adopted.

In each analysed case, the nodal load of the bracing was calculated as specified by standard [7]. These values are given in square brackets in Figs. 6, 7, 8 and 9.

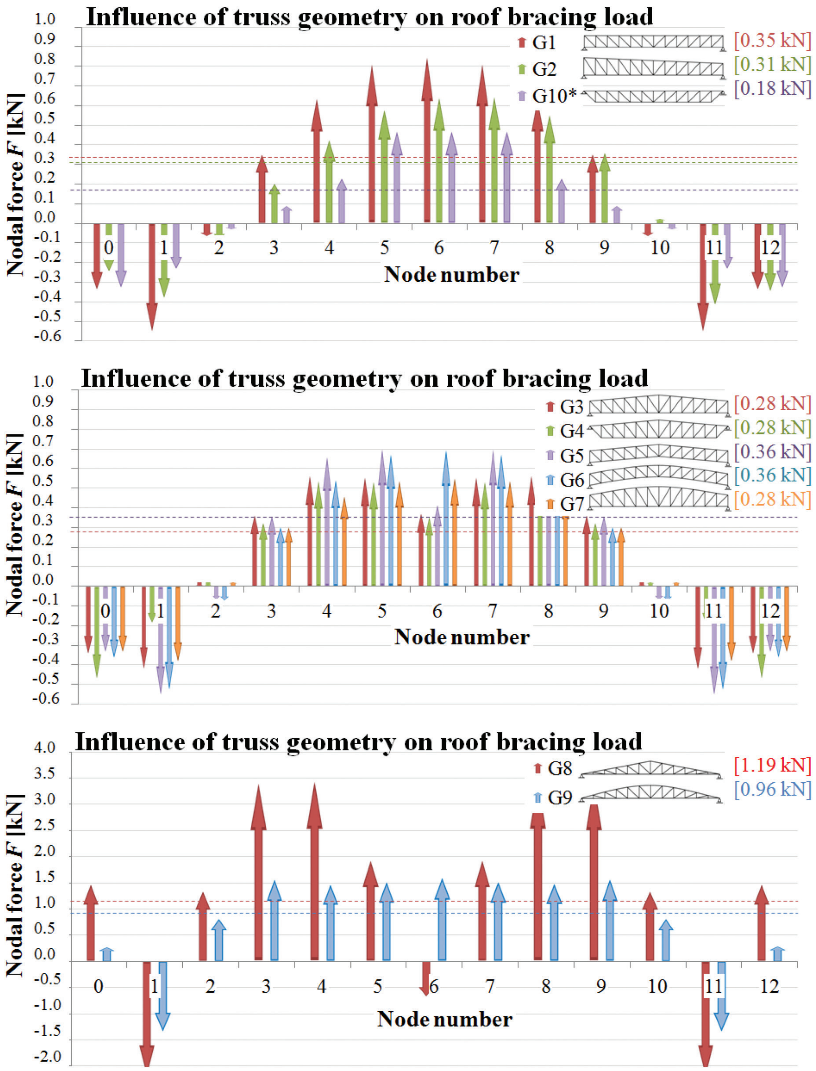


Fig. 6. Influence of truss geometry on roof bracing load

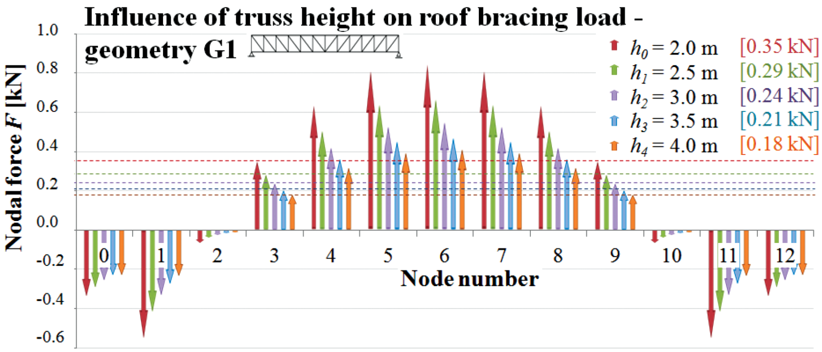


Fig. 7. Influence of truss height on roof bracing load

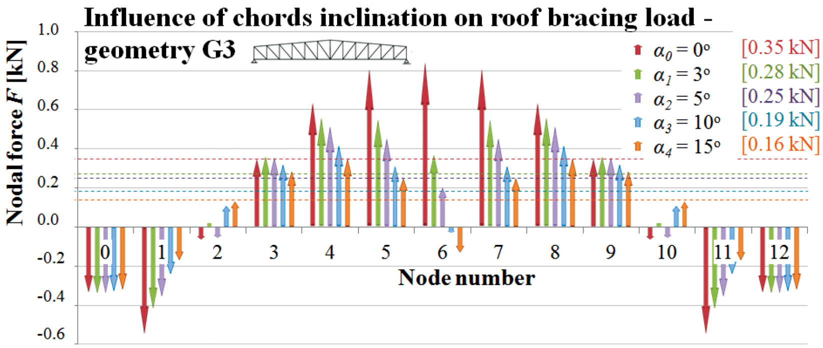


Fig. 8. Influence of chords inclination on roof bracing load

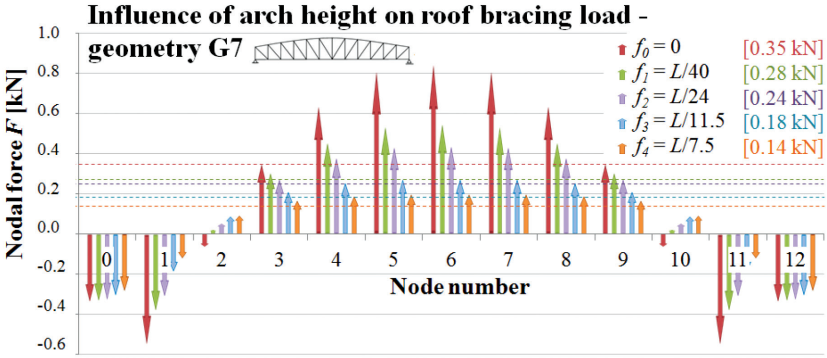


Fig. 9. Influence of arch height on roof bracing load

3. Results

The results of the numerical analyses are presented in Tables 1–4, in which the load of roof bracing F_n [kN] is included. Considering the symmetry of loads in most results, only the results for nodes 0-6 are provided. Selected results were translated to graph form in order to determine the influence of particular parameters. Table 1 presents the load of roof bracing in the case of different geometries of truss girders and with the basic values of truss/arch height as well as roof inclination. The positive load values shown in the tables and graphs are complies with standard load sign.

Table 1. Test results – Influence of geometry ($h = 2.0$ m, $\alpha = 3^{\circ}$; $f = L/40$) [kN]

Geometry	Node number						
	0	1	2	3	4	5	6
G1	–0.34	–0.55	–0.07	0.35	0.64	0.81	0.85
G2	–0.24	–0.38	–0.08	0.20	0.43	0.58	0.64
G3	–0.34	–0.42	0.02	0.36	0.57	0.56	0.37
G4	–0.47	–0.18	0.02	0.33	0.54	0.54	0.35
G5	–0.34	–0.56	–0.07	0.36	0.66	0.70	0.41
G6	–0.36	–0.53	–0.07	0.30	0.54	0.67	0.70
G7	–0.34	–0.39	0.02	0.30	0.46	0.54	0.55
G8	1.47	–2.18	1.34	3.41	3.44	1.93	–0.67
G9	0.28	–1.34	0.81	1.57	1.58	1.53	1.61
G10*	–0.33	–0.23	–0.03	0.09	0.26	0.47	0.47

The findings concerning the influence of truss height on the load of roof bracing are presented in Table 2. The analysis was conducted in the case of G1 geometry and the following truss heights were considered: $h_0 = 2.0$ m; $h_1 = 2.5$ m; $h_2 = 3.0$ m; $h_3 = 3.5$ m; $h_4 = 4.0$ m.

Table 2. Analysis results – Influence of truss height [kN]

Height	Node number						
	0	1	2	3	4	5	6
h_0	–0.34	–0.55	–0.07	0.35	0.64	0.81	0.85
h_1	–0.29	–0.42	–0.04	0.28	0.51	0.64	0.67
h_2	–0.26	–0.34	–0.03	0.24	0.41	0.53	0.55
h_3	–0.23	–0.28	–0.02	0.21	0.36	0.45	0.47
h_4	–0.21	–0.24	–0.01	0.18	0.32	0.41	0.41

Analysis results regarding the influence of the inclination of the truss chord on the load of roof bracing are presented in Table 3. In this case, G3 geometry was adopted as the basic geometry. The following inclination angles were considered in the analysis: $\alpha_0 = 0°$; $\alpha_1 = 3°$; $\alpha_2 = 5°$; $\alpha_3 = 10°$; $\alpha_4 = 15°$.

Table 3. Analysis results – Influence of chords inclination [kN]

Inclination	Node number						
	0	1	2	3	4	5	6
α_0	–0.34	–0.55	–0.07	0.35	0.64	0.81	0.85
α_1	–0.34	–0.42	0.02	0.36	0.57	0.56	0.37
α_2	–0.34	–0.36	0.06	0.36	0.52	0.46	0.20
α_3	–0.33	–0.24	0.11	0.32	0.42	0.32	–0.03
α_4	–0.32	–0.17	0.13	0.29	0.35	0.25	–0.13

The analysis results regarding the influence of arch height of truss on the load of roof bracing are presented in Table 4. In this case, G7 geometry was adopted as the basic geometry. The following arch heights: $f_0 = 0; f_1 = L/40; f_2 = L/24; f_3 = L/11.5; f_4 = L/7.5$ were considered in the analysis.

Table 4. Analysis results – Influence of arch height [kN]

Arch height	Node number						
	0	1	2	3	4	5	6
f_0	–0.34	–0.55	–0.07	0.35	0.64	0.81	0.85
f_1	–0.34	–0.39	0.02	0.30	0.46	0.54	0.55
f_2	–0.33	–0.31	0.05	0.27	0.38	0.43	0.44
f_3	–0.31	–0.19	0.09	0.21	0.26	0.27	0.27
f_4	–0.28	–0.12	0.09	0.17	0.19	0.20	0.20

The results presented in Tables 1–4 are displayed in graph form in Figs. 6–10.

The results regarding the influence of truss girder geometries on the load of roof bracing (Fig. 6) are in good agreement with the results of theoretical analyses [3, 6] and experimental research [8]. In all cases, non-uniform distribution of bracing's load with the sign-changing points near the supports was occurred. In all studies, the maximum values of nodal load are higher than the values specified by standards.

It should be pointed out that in the case of the G3, G4, G5 geometries, a noticeable reduction of nodal load in the middle of the span was observed. This is connected with the ridge of the upper chord. In the case of the G6 and G7 geometries, the alignment of load distribution occurs in the middle of span.

The cases of G8 and G9 geometries, which are presented in Fig. 6, show significant changes in the distribution of the load of roof bracing. In the case of the G8 geometry, an additional sign changing of the nodal load in the ridge was observed. However, in the case of the G9 geometry, a quasi-uniformly distributed load (approximately 150% of the value of standard load) occurred across the whole mid-span of truss.

According to the paper [6], inclination of the truss which results from the curvature of the upper chord has a major influence on the bracing's load. The resulting twisting angle of the truss cross section depends on truss height. The influence of the height of the truss with the G1 geometry on the load of roof bracing (Fig. 7) is characterised by a non-uniform reduction in each node. The biggest reduction occurs in trusses of insignificant height. However, in the case of trusses higher than 3.0 m, this influence is negligible.

In the case of trusses with non-parallel chords, the distribution of compression force in the upper chord is different than the quasi-parabolic distribution. It was reflected in the distribution of the load of roof bracing (Fig. 8) by reducing the value of nodal load in the ridge area. Regarding the analysed trusses with the chord inclination angle above 10°, additional sign changing of load occurred in the ridge node.

The most significant influence of the upper chord arch height on the nodal load of the roof bracing was observed in the mid-span zone of truss. An increase in arch height was accompanied by alignment of nodal load in this zone. In the analysed truss with an arch height of $f_4 = L/7.5$, the value of nodal load in all the nodes from 3 to 9 was approximately 140% of the value of standard load.

4. Roof bracing

The above-determined the load of roof bracing resulting from truss girder imperfection was applied to the transverse roof bracing of the hall structure shown in Fig. 10. Ten truss frames ($m = 10/2$) with the spacing $l = 6.0$ m and two X-type bracings located in the first and last sections of the hall were adopted. As recommended by the standard [7], the relevant value of reduction

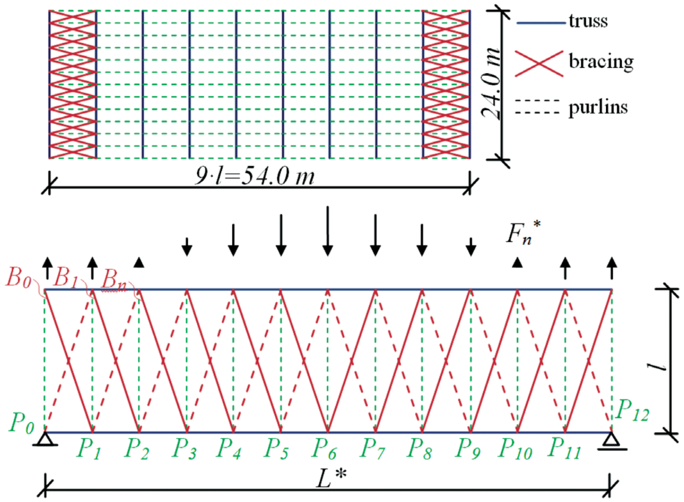


Fig. 10. Adopted hall structure and bracing geometry

coefficient α_m was used. The bracing length L^* was calculated as the length of the upper chord in the relevant cases of geometry. Circular rods with a diameter of $\phi = 20$ mm as bracing rods and a IPE 180 I-section rods as purlins were adopted. The value of nodal load applied to the bracing $F_n{}^*$ was calculated in accordance with the procedure set in the EN 1993-1-1 standard $(F_n{}^* = F_n \cdot \alpha_m \cdot m)$.

Both sign-changing distribution of the of the roof bracing and higher values of nodal load have an impact on the load of particular elements of bracing and purlins. The relevant values of the forces in bracing rods and purlins for selected cases of geometry were determined by means of numerical analysis performed on a model built of beam-type elements. The analyses were conducted using the SOFiSTiK program [9] by applying a geometrically non-linear analysis of the bracing model presented in Fig. 12. Bracing rods were modelled as cable elements. The results regarding the load of particular elements of the bracing model are presented in Tables 5 and 6.

Table 5. Numerical analysis of separated roof bracings – load of purlins

Geometry	**Purlin number**						
	0	**1**	**2**	**3**	**4**	**5**	**6**
G1 (h_0)	4.86 (7.99)	6.09 (7.29)	8.12 (6.01)	8.42 (4.67)	7.12 (3.34)	4.69 (2.00)	3.22 (1.33)
G1 (h_4)	2.51 (4.11)	3.28 (3.75)	4.17 (3.09)	4.22 (2.40)	3.55 (1.72)	2.34 (1.03)	1.56 (0.68)
G2	3.22 (7.08)	4.09 (6.45)	5.50 (5.32)	5.82 (4.13)	5.08 (2.96)	3.44 (1.77)	2.42 (1.18)
G3 (α_1)	3.59 (6.39)	4.83 (5.83)	6.39 (4.80)	6.34 (3.73)	5.00 (2.67)	2.86 (1.60)	1.48 (1.06)
G3 (α_4)	1.78 (3.65)	2.98 (3.33)	3.60 (2.75)	3.13 (2.13)	2.04 (1.53)	0.91 (0.91)	–0.09 (0.61)
G4	3.65 (6.39)	5.40 (5.83)	6.07 (4.50)	6.00 (3.73)	4.77 (2.67)	2.074 (1.60)	1.37 (1.06)
G5	3.68 (8.22)	4.91 (7.50)	6.98 (6.18)	7.28 (4.80)	5.94 (3.43)	3.47 (2.06)	1.62 (1.36)
G6	3.47 (8.22)	4.78 (7.50)	6.74 (6.18)	7.04 (4.80)	5.92 (3.43)	3.87 (2.06)	2.65 (1.36)
G7 (f_1)	3.32 (6.39)	4.56 (5.83)	6.01 (4.80)	5.97 (3.73)	4.84 (2.67)	3.10 (1.60)	2.09 (1.06)
G7 (f_4)	1.34 (3.20)	2.38 (2.91)	2.83 (2.40)	2.51 (1.87)	1.87 (1.33)	1.14 (0.80)	0.76 (0.53)
G8	34.84 (27.2)	28.77 (24.8)	36.78 (20.4)	32.09 (15.9)	19.32 (11.4)	7.13 (6.8)	–0.59 (4.5)
G9	20.09 (21.9)	18.84 (20.0)	23.71 (16.5)	20.87 (12.8)	14.94 (9.2)	8,90 (5,5)	6,09 (3,6)
G10*	1.75 (3.99)	2.88 (3.57)	3.68 (0.62)	3.81 (2.99)	3.47 (2.33)	2.55 (1.00)	1.74 (0.66)

Table 6. Numerical analysis of separated roof bracings – load of bracing rods

Geometry	rod number					
	0	**1**	**2**	**3**	**4**	**5**
G1 (h_0)	−6.50 (−7.61)	−8.56 (−6.33)	−8.86 (−4.91)	−7.47 (−3.51)	−4.94 (−2.11)	−1.66 (−0.69)
G1 (h_4)	−3.49 (−3.91)	−4.39 (−3.26)	−4.45 (−2.52)	−3.73 (−1.80)	−2.46 (−1.08)	−0.81 (−0.35)
G2	−4.37 (−6.74)	−5.80 (−5.61)	−6.13 (−4.35)	−5.33 (−3.11)	−3.63 (−1.87)	−1.28 (−0.61)
G3 (α_1)	−5.16 (−6.09)	−6.72 (−5.07)	−6.67 (−3.93)	−5.24 (−2.81)	−2.99 (−1.69)	−0.76 (−0.55)
G3 (α_4)	−3.17 (−3.48)	−3.78 (−2.90)	−3.29 (−2.24)	−2.14 (−1.60)	−0.74 (−0.96)	−0.17 (−0.31)
G4	−5.72 (−6.09)	−6.41 (−5.07)	−6.31 (−3.93)	−5.00 (−2.81)	−2.87 (−1.69)	−0.72 (−0.55)
G5	−5.26 (−7.83)	−7.35 (−6.52)	−7.66 (−5.05)	−6.23 (−3.61)	−3.62 (−2.17)	−0.86 (−0.71)
G6	−5.12 (−7.83)	−7.10 (−6.52)	−7.41 (−5.05)	−6.22 (−3.61)	−4.08 (−2.17)	−1.37 (−0.71)
G7 (f_1)	−4.88 (−6.09)	−6.32 (−5.07)	−6.28 (−3.93)	−5.09 (−2.81)	−3.26 (−1.69)	−1.08 (−0.55)
G7 (f_4)	−2.54 (−3.04)	−2.97 (−2.53)	−2.64 (−1.96)	−1.96 (−1.40)	−1.20 (−0.84)	−0.39 (−0.27)
G8	−30.72 (−25.9)	−38.69 (−21.5)	−33.58 (−16.7)	−20.19 (−11.9)	−6.51 (−7.2)	−0.70 (−2.3)
G9	−20.01 (−20.9)	−24.88 (−17.4)	−21.91 (−13.5)	−15.70 (−9.6)	−9.39 (−5.8)	−3.14 (−1.9)
G10*	−3.15 (−3.65)	−3.86 (−3.14)	−4.02 (−2.44)	−3.65 (−1.74)	−2.62 (−1.05)	−0. 86 (−0.33)

In each case, the load of a particular member, which was determined on the basis of the standard value of the bracing's load, is given in brackets. In both Tables 5 and 6, longitudinal compression force is indicated by a '+' sign.

5. Conclusions

Nodal load distributions of transverse roof bracing resulting from the geometrical imperfection of truss girders (presented in Figs. 6–11) show strong agreement with the theoretical and experimental analyses. The analysed truss geometries have a negligible influence on the nodal load distribution of roof bracing. In most cases, load distribution approximates the load distribution obtained in the truss with parallel chords (G1). Only in the case of the triangular truss (G8) can a change in load distribution characterised by multiple sign changing be observed.

An increase in truss height (in the case of the G1 geometry) reduces the value of the nodal load, which results from the evident reduction of compression force in the upper chord and the reduction of the twisting angle of the truss cross section. This angle depends on shape of chord imperfection. Therefore, this influence is the highest in the central part of the truss.

Considerable influence of the chord ridge (G3, G4, G5) and curvature (G6, G7) has been observed. The influence of the compressed chord's ridge manifests itself in the reduction of nodal load on the roof bracing in the ridge area. An increase in chord inclination (above 10°) considerably influences the reduction of load, which may lead to its sign changing. The influence of the curvature of the compressed chord manifests itself by alignment of the load values in the central part of truss. Increasing the upper chord arch height to the value of $f = L/7.5$ leads to the alignment of nodal load values in the entire central part of the truss (ranging from $0.25L$ to $0.75L$).

Load distribution of transverse roof bracing influences the distribution of longitudinal force in purlins and bracing rods. In the case of bracing load distribution specified by the standard (uniform distribution), eaves purlins (P0) and bracing rods in extreme fields (B0) are the most loaded. The non-uniform distribution of load obtained in the analysed cases increases the load of purlins and bracing rods in the area of load sign changing (purlins P2, P3 and bracing rods B1, B2).

In the case of non-uniform distribution, the maximum compression forces in purlins resulting from numerical analysis are 8.42 kN in the case of the G1 geometry and 36.78 kN in the case of the G8 geometry. These forces are similar to the maximum load of purlins in the case of the standard load. They constitute 16 and 70% respectively of the out-of-plane buckling resistance for compression of the analysed purlin.

The maximum values of tensile force in bracing rods are 8.86 kN in the case of the G1 geometry and 38.69 kN in the case of G8 geometry. These values, which are higher than the values of the forces obtained in the case of standard load (in the case of the G1 geometry, up to 16%, and in the case of the G8 geometry, up to 50%). They constitute 12 and 52% respectively of the bracing rod's tension resistance. It should therefore be recognised that they contribute to ensuring safety of the designed element.

None of the obtained load distributions approximate the distribution indicated by the EN 1993-1-1 standard. It can therefore be concluded that, in the case of currently designed trusses with diverse geometries, standard recommendations are confusing for designers and lead to the erroneous estimation of load for particular purlins and bracing rods. This explains why EN 1993-1-1 regulations should be verified. This can be achieved by changing the shape and the value of the bracing standard load distribution or by replacing the simplified flat model with the spatial model. This model should include a separated fragment of a hall (most often two main frames) and its existing roof bracings, vertical truss girder bracings and wall bracings.

References

[1] Biegus A., *Trapezoidal sheet as a bracing preventing from out-of-plane buckling*, Archives of Civil and Mechanical Engineering 15/2015, 735–741.

[2] Biegus A., Czepiżak D., *Analytical and numerical research of equivalent stabilizing force of stiffened truss chords*, Matec Web of Conferences 262/2019.

[3] Czepiżak D., Biegus A., *Refined calculation of lateral bracing systems due to global geometrical imperfection*, Journal of Constructional Steel Research 19/2016, 30–38.

[4] Niewiadomski L., Zamorowski J., *The load of transversal bracings resulting from geometric imperfection of single-span trusses of roofs*, Proceedings of the 12th International Conference on New Trend in Static and Dynamics of Buildings, Bratislava, Slovakia, 2014. [in Polish]

[5] Pałkowski S., *The calculation models of transversal roof bracings*, Inżynieria i Budownictwo 3/2016, 131–133.

[6] Pałkowski Sz., Piątkowski M., *On the calculation of lateral roof bracing*, Inżynieria i Budownictwo 4/2014, 210–213.

[7] PN-EN 1993-1-1: 2006. Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for building.

[8] Piątkowski M., *Impact of truss girder geometrical imperfections on roof bracing load*, Matec Web of Conferences 262/2019.

[9] SSD SOFiSTiK Structural Desktop, User interface of SOFiSTiK, SOFiSTiK AG, 2008.

If you want to quote this article, its proper bibliographic entry is as follow: Piątkowski M., *The influence of the geometry of imperfect trusses on the loading of transversal roof bracings*, Technical Transactions, Vol. 9/2019, pp. 119–132.