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Slovak Journal of Civil Engineering
Vol. 31, 2023, No. 1, 1 – 9
DOI: 10.2478/sjce-2023-0001

A COMPARISON OF CADASTRE IN SLOVAKIA AND POLAND

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Abstract

Many analogies can be drawn from the cadastre in Poland and Slovakia, because of the partly shared history of the Austro-Hungarian Empire, World Wars I and II, and the influence of the Communist regime. However, its development over the years has taken different forms and rules of operation in both countries. Currently, from a European perspective, there are efforts to standardise cadastral systems to expand their functionality for land administration and to accommodate social needs.
The aim of this article is to discuss and provide a detailed comparative analysis of the general principles of the cadastre in Slovakia and Poland. The study shows similarities but also many differences between the systems in both countries, which indicates that it could be a difficult path to unify the cadastral systems within the European Union. A comparison of the solutions used in other countries allows us to see potential opportunities for the development and modernisation of the existing cadastral systems.

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Key words

- Real estate cadastre,
- Land and property register,
- Land and mortgage registers.

1 INTRODUCTION

According to the International Federation of Surveyors (FIG), a cadastre is a database register of areas with an inventory of *in rem* rights in a parcel of land. It contains a geometric description of the plots of land linked to other registers that constitute the nature of these rights and often the value of the plot and any relevant changes to it. The cadastre is run for fiscal and legal purposes as well as to support spatial management and enable the development of the land and environmental protection (FIG 2011).

The legal acts and technical standards for the implementation of the cadastral institution and its functioning are different in each country. Thanks to being able to easily obtain information about solutions used abroad, it is possible to implement new and functional solutions in this field in one's own country.

Different principles of creating a modern cadastre are often dictated by various historical conditions that have existed over the years. In addition, the possibilities of financing cadastral reforms as well as technological and organisational conditions in a given country are important. The cadastre in Poland and Slovakia underwent a great deal of changes through many years of partitions, World Wars I and II, and then the years of the communist regime (Mika, Siejka 2012). Moreover, in Poland, different historical conditions in different regions significantly influenced the heterogeneous quality of the cadastral data in individual areas of the country (Buśko, Meusz 2014). The system currently in force in Poland began to take shape after World War II and adopted its final rules after the economic and political transformations of 1989. Similarly, in Slovakia, a new cadastral system was developed in 1993 after the partition of the Czechoslovak Federal Republic (Vlček 2005).

Both countries deal with many legal, organisational, and technical issues in the cadastral area. One of the main problems in the cadastral system of Slovakia is the quality of the cadastral maps, which have different origins. More than half of the maps do not meet the current requirements for real estate registration, and their modernisation is necessary (Hudecova, Kysel 2020). The situation is similar in Poland, where the legal regulations are constantly being updated; however, many shortcomings and gaps in the source materials that are used for geodetic measurements, including cadastral measurements, are still a significant problem (Mika 2016).

Current works on the development of cadastral systems in the European Union countries are dictated by the implementation of international technical regulations and standards. In 2007, the European Union adopted the INSPIRE Directive (INSPIRE 2007), which established an infrastructure for spatial information in the Union. In turn, in 2012, the International Organisation for Standardisation published the ISO 19152 standard on property management, i.e., the Cadastral Model of Land Administration (LADM 2012), which addresses the issue of standardising the principles of creating and maintaining cadastral systems. The EU member states are obliged to comply with this European law.

The aim of this article is to set out a comparative analysis of the principles of the real estate cadastre currently functioning in Slovakia and Poland. The comparisons were made on the basis of an analysis of the legal acts in force in both countries and of other available source materials, including the Polish and Slovak geoportal, electronic land, and mortgage registers. The comparative analysis concerns two countries that share some common history and the genesis of the cadastral system, but their development has varied. A comparison of the solutions used in other countries allows us to see potential opportunities for the development and modernisation of the existing cadastral systems. This is particularly important in terms of the desired state of integration of the land register and the legal register in the cadastral system.

The aim of the article is also to show the similarities and differences that can contribute to the modernization of the existing systems in Poland and Slovakia. This is particularly important in the context of efforts to unify cadastral systems within the European Union. An important aspect is the fact that Slovakia has an integrated cadastral system that combines a land register and a rights register. In Poland, the integration of these registers is still an ongoing challenge; therefore, drawing on the experience of a neighbouring country can help in the organisation and harmonisation of its registers.

2 THE RANGE OF THE BASIC LEGAL ACTS OF THE REAL ESTATE CADASTRE DATA IN SLOVAKIA

In Slovakia, there are two main legal acts that regulate the functioning of the real estate cadastre, i.e., the Act of the National Council of the Slovak Republic of 27 June 1995 on the real estate cadastre and on the registration of ownership and other rights to real estate (“the Cadastral Act”) (Act 1995) and the Ordinance of the Geodesy, Cartography and Cadastre Authority of the Slovak Republic, which implemented the Act of the National Council of the Slovak Republic No. 162/1995 Coll. on the real estate cadastre and on the registration of ownership and other rights to real estate (Regulation 2009).

According to the Cadastral Act (Act 1995 §1, §2), **a real estate cadastre** is defined as a geometric designation, a list, and the characteristics of real estate together with data on the rights to such real estate. It serves as an information system, which is used in particular for the protection of real estate rights, tax purposes, and purposes of real estate appraisal and other aspects of land and forest real estate management. It is a public and open register, and the information it contains is available to everyone. As a fully-fledged system, the Slovak cadastre contains both descriptive and geometric data about real estate (cadastral maps) and data on the rights of various entities to this real estate, as well as real estate prices if this information is available on the basis of specific documents (Regulation 2009 §13a). The rights that are registered in the cadastre are listed in the Cadastral Act (Act 1995 §1) and consist of: ownership; liens; rights of easement; and rights of pre-emption, if they are to have the effect of a right *in rem*; rights resulting from the administration of state and municipal property and higher territorial units, and land lease rights, if they are to last at least 5 years.

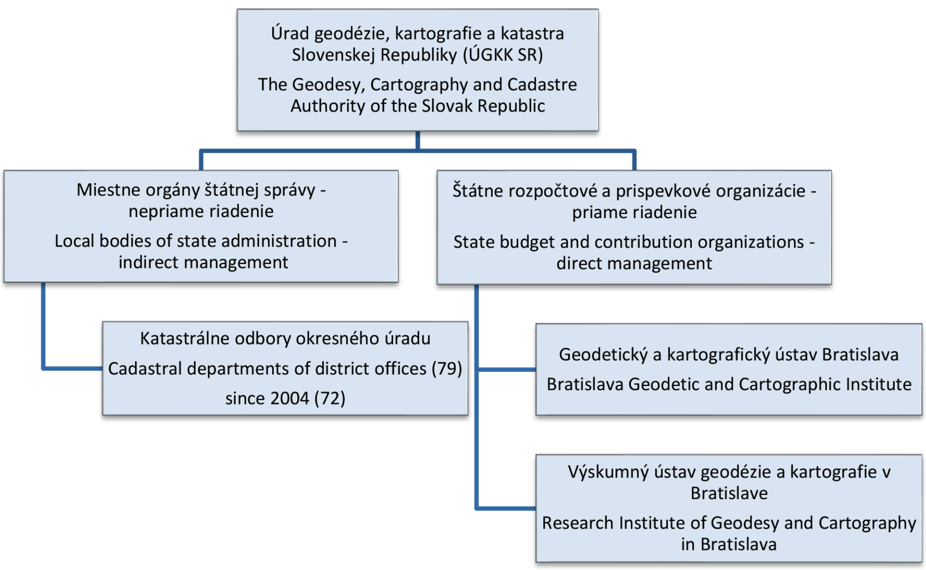

Fig. 1 *Organisational structure of the cadastre in Slovakia* Source: https://www.skgeodesy.sk/en/

The identification data of the property owner or other authorised persons who have certain rights to the property is also provided. Such a person may be a pledgee, someone entitled to pre-emption rights, someone entitled to an easement, a tenant, an administrator of state property, a higher territorial or municipal unit, the Slovak Land Fund, or a forest land administrator (Act 1995 §3a).

The detailed scope of the descriptive information characterising cadastral real estate is regulated by the ordinance (Regulation 2009) to the Cadastral Act. In the field of real estate, the following data are recorded in the cadastre: the plot number, surface area, information on the location of the plot in built-up areas of the community, type of land, type of land use, the soil valuation class, and data on the type of protected property. As a part of the real estate of buildings, these include: the registration number of the building, the number of the plot on which the building is built, the building type code, the building location code (above-ground or underground), and data on the type of protected property. As to housing properties, the reference number of the building, the entrance number, the floor number, the apartment number, the type of apartment code, the type of non-residential premises code, and the share in the common parts of the building and land are required. In addition, for all types of real estate, the number of the deed of ownership is recorded and, if available, data on real estate prices on the basis of binding documents.

A cadastral map is a graphic representation of the real estate in the cadastral system. It is defined as a large-scale planimetric map showing all the real estate and cadastral areas registered in the cadastre. The lands are presented on the map by projecting their boundaries onto a projection plane and are marked with plot numbers and the type of land symbol (Act 1995 §3). Properties are represented by their geometric definition (shapes and dimensions) and locations on a specific coordinate system.

The central body of state administration in the field of cadastre is the Geodesy, Cartography and Cadastre Authority of the Slovak Republic. It is responsible for district offices (okresné úrady), which are local administrative bodies that effectively administer the cadastral system (Act 1995 §11). The detailed structure of the cadastre organisation in Slovakia is presented in Figure 1.

3 CHARACTERISTICS OF THE FUNCTIONING OF THE CADASTRE IN SLOVAKIA

The cadastral system is based on real estate, which, according to the Slovak Civil Code (Act 1964A § 119), is land or a building erected on a solid foundation. According to the Cadastral Act (Act 1995 §6), land, buildings, underground structures, flats and non-residential premises, as well as buildings, flats and non-residential premises under construction are treated as cadastral real estate. In the Slovak cadastre, in contrast to the Polish one, the Roman principle of *superficies solo cedit* (what is on the surface becomes the ground) does not apply. Thus, each building built on a solid foundation is a separate property. The underground strucures are recorded at their points of intersection with the Earth's surface.

The cadastre registers land that is distinguished by the boundaries of ownership, possession, the type of land, the method of use, the cadastral area or built-up area of a commune. Thus, land belonging to one owner, but if it separated by one of the above-mentioned boundaries, it constitutes a separate plot (Act 1995 §6).

A cadastral parcel is the basic unit of a country's surface cadastral division. A plot is defined as land defined in terms of its geometry (dimensions and shape) and position (on the coordinate system) and as presented on a cadastral map, a map of the site or a geometric plan with the number of the plot (Act 1995 §3).

There are plots "C", which are shown on a cadastral map, and "E", which are presented on a map of the former documentation. This division results from historical conditions. "E" plots are plots originally registered at the time of the establishment of the land and mortgage registers. During the creation of the new cadastral system in the post-War period (after 1950), the registration of "C" plots was started, the boundaries of which are measured and stabilised in the field, and thus are legally binding according to the public authorities and have a specific actual use. In "E" plots the type of use usually does not correspond to the actual use, and the boundaries of these plots and their surface area can no longer be identified in the field. They should be converted into "C" parcels (areas) through geodetic measurements (Kakusová 2021).

Plots are numbered with natural numbers. After the division of a newly separated plot, another free natural number is added to the denominator, thus creating a fraction. The number of the divided plot remains the same; however, its area and some border points can change (Guideline S 74.20.73.43.00). This situation is shown in Figure 2. The plot of No. 189/1 is divided. After the division, one of the plots receives a new number, i.e., 189/3, and the other keeps the existing number, i.e., 189/1. If a plot number fraction is already being used (i.e., 189/2), the next free number in order is used (i.e., 189/3).

According to the Cadastral Act (Act 1995 §3), the plot boundary is defined by break points. These are the points where there is a break in the boundary of the ownership or the type of land or land use. The boundary of adjacent plots of land limited by ownership is considered to be the actual possession boundary if it is not disputed between the neighbours.

The breakpoints of property boundaries, land-use boundaries, and the projections of buildings measured during

Fig. 2 *Numbering of plots after 189/1 division in Slovakia.*
Source: *authors' study*

geodetic works must be determined in the S-JTSK coordinate system (Súradnicový systém Jednotnej trigonometrickej siete katastrálnej) with the quality T = 1, i.e., with a basic mean coordinate error m_{xy}= 0.08 m specified in the regulation (Regulation 2009) to the Cadastral Act. Border points are marked with a permanent border mark made of concrete, iron or plastic, if all the owners agree to the designated location of these boundary points. If not, a temporary sign should be used (Regulation 2009 §§44, 53).

The basis for the functioning of the cadastral system are cadastral surveys conducted for individual cadastral parcels (Act 1995 §3). Cadastral parcels most often refer to the area of one precinct (obec), i.e., the basic territorial division unit of the country. It is also common for several cadastral districts to be included in the same area.

The cadastral documentation consists of the following parts (Act 1995 §8):

- a file of the survey data – a cadastral map,
- a set of descriptive information about the cadastral objects, the rights to them, the owners and other entitled persons, and data from the ownership deed,
- a set of documents constituting the basis for the entry in the cadastre,
- a summary of the data on the Land Fund,
- land and mortgage registers, railway registers and their reports serving as a source of cadastral data.

An extract, an excerpt or a copy of the cadastral documentation, an excerpt from the land register or the designation of the plot is made available on behalf of the Geodesy, Cartography and Cadastre Authority of the Slovak Republic by the competent district offices. Upon request, the owner can also obtain information on the price of the property. The data may be made available in paper or electronic form (Act 1995 §§68, 69).

According to §§4 and 5 of the Cadastral Act (Act 1995), entry to the cadastre is made on the basis of documents, just as in Poland. Rights to real estate are introduced in the form of a deposit (vklad), which causes a change in or expiry of the right to the real estate, or are in the form of an entry (záznam), which registers matters settled by another authority and does not affect the creation, change or expiry of the ownership right.

The validity of cadastral data is ensured by the district offices, which regularly examine reported or otherwise identified changes in this data. Moreover, the offices may verify compliance with the legal status and the facts of the cadastral

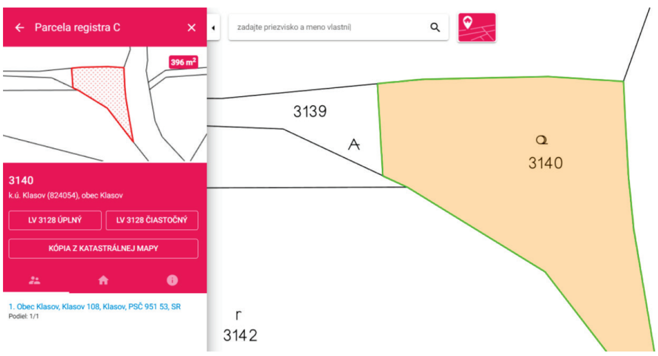

Fig. 3 *Fragment of the Slovakia geoportal.*
Source: *https://zbgis.skgeodesy.sk/*

data. This procedure is carried out with the participation of state and municipal authorities and owners (Act 1995 §§57, 67a).

The information contained in the Slovak Real Estate Cadastre is publicly available through the internet portal https://zbgis.skgeodesy.sk/. On the website, you can view a country-wide cadastral map and information on property owners (Figure 3), as well as download a map extract and a complete or partial excerpt from the cadastre.

4 BASIC LEGAL ACTS AND REGISTERS IN THE FIELD OF REAL ESTATE CADASTRE IN POLAND

Information on real estate in terms of the subject (property rights) and the structure (land, building, premises) is collected in Poland via two basic registers: land and building records and land and mortgage registers.

The legal acts regulating the matters of land and building registration are the Act of May 17, 1998, The geodetic and cartographic law (Act 1989), and its executive act – the ordinance of 27 July 2021 on land and building records (Regulation 2021).

The Land and Property Register (LPR) currently plays the role of a cadastre in Poland until it is transformed into a full-fledged cadastre (Act 1989 art. 53a) in accordance with Art. 2, point 8, of the Geodetic and Cartographic Law (Act 1989), an information system ensuring the collection, updating and sharing, in a uniform manner for the country, of information on land, buildings and premises and their owners and other entities that own or manage this land, buildings or premises. Within the scope of the descriptive data, information on registration plots is recorded, i.e., the location, data on boundaries, area, types of land use and their valuation classes, designations of land and mortgage registers or files of documents. In terms of buildings, these are their location, purpose, utility function, and technical data, and in terms of premises, these are the location, utility function and usable area (Act 1989, Art. 20).

A cadastral map is a data visualisation of the land and building register database. The content of the map graphically presents the location and geometry of plots through a numerical description of their boundaries, as well as the contours of the land use, valuation classes, and the contours of buildings. In addition, the numbers of plots and building designations, as well as the boundaries of the units of the basic three-tier territorial division of the country, are recorded (Regulation 2021 §26).

Another register is **the Land and Mortgage Registers** (LMR), which are established and maintained for each property in order to establish its legal status. The issues of the land and mortgage register are regulated by the Act of 6 July 1982 on Land and Mortgage Registers and Mortgages (Act 1982).

The land and mortgage registers consist of 4 sections: section I consists of two parts, i.e., the I-O designation of the real estate, and I-Sp, i.e., a list of a rights related to property; section II contains a designation of entities with rights to the real estate; section III contains entries of limited property rights, limitations in the disposal of real estate and other claims and rights, except for mortgages; and Section IV concerns the entry of a mortgage (Act 1982, Article 25). Since 2010, LMR has been run in the information and communication

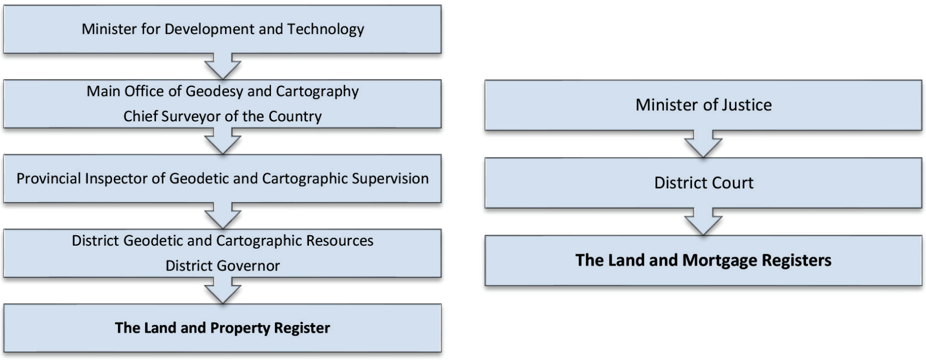

Fig. 4 *Scheme of geodetic and cartographic services in the field of cadastre in Poland.* Source: *authors' study based on the Acts of 1989 and 1982*

technology (ICT) system in accordance with the Regulation of the Minister of Justice of February 15, 2016, on the establishment and maintenance of land and mortgage registers in the ICT system (Regulation 2016).

The information from the aforementioned registers is interrelated, i.e., the basis for entries in the Land and Mortgage Register regarding descriptive and graphic information about land, buildings and premises are data obtained from the Land and Building Register, while the Register includes a reference to the Land and Mortgage Register in order to access information on the legal status of a given plot (Act 1982, Article 26). Information from the Land and Mortgage Register with the exception of section I-O, is covered by a warranty of public faith in order to secure the rights registered there (Act 1982, Article 5).

The rights that are registered in the land and mortgage registers are: ownership, joint ownership, perpetual usufruct, and limited property rights, i.e., usufructs, easements, pledges, cooperative ownership rights to premises, and mortgages.

The structure of geodetic and cartographic services in Poland consists of supervisory and administrative bodies. The Land and Buildings Register is kept by state administration bodies or mayors of cities with district rights for the areas of individual districts. In turn, LMR is subject to local district courts, the jurisdiction of which covers several communities, but is not consistent with the territory of the district. Figure 4 shows a simplified diagram of the structure of the administration and supervision of the cadastral database in Poland.

5 CHARACTERISTICS OF THE FUNCTIONING OF THE CADASTRE IN POLAND

In the Polish cadastral system, there is a dualism involving the basic structure to which the land and building registers and land and mortgage registers relate. In the Land and Building Register, the basic unit is a recorded plot, building or premise. On the other hand, the Land and Mortgage Register includes real estate and real estate for buildings and premises.

As stipulated in the Civil Code (Act 1964B art. 46), **real estate** is a part of the land constituting a separate subject of ownership (land), as well as buildings permanently connected with the land or parts of such buildings; if they are under special provisions, they constitute an object of ownership separate from the land. Therefore, in Poland, there is a Roman rule assigning buildings located on specific land to the land.

The land registration units of the country division are the:
– registration unit,
– registration area,
– registration plot.

A registration unit that constitutes an area of an urban, rural or urban-rural community is divided into registration areas, which may constitute part of or the entire area of a village or city. The precinct, which in rural areas covers an the entire village, and in urban areas, a city or a part of it, is divided into registration plots (Regulation 2021 §5, §6).

Therefore, **the land plot** is the basic area of the Land and Building Register. A land plot is a continuous area of land located within one registration precinct; it is legally homogeneous and separated from the surroundings by the boundaries of the registration plots (Regulation 2021 §7). They must be located in an area covered by a given district court, which may include one or more registration units.

Plots are numbered in the form of natural numbers. After a division, the denominator is added to the plot number, which is the smallest natural number that allows for each separated plot to be distinguished (Regulation 2021 §7). An example of the numbering of plots after the division is shown in Figure 5. In the case of merging plots, the next free number within the registration area is used.

Fig. 5 *Numbering of plots after the division of the plot 189/1 in Poland.* Source: *authors' study based on the Regulation (2021).*

The boundary of the area of registration is defined in the regulation on the registration of land and buildings (Regulation 2021 §2) as a broken line or a section common to the neighbouring areas. Border sections are defined by border points, which should be designated as details of group I, with an accuracy of not less than 0.10 m (Regulation 2020).

The data collected in the land and building records are included in the inventory, which is kept by the competent district authority office. It includes:

– a database of land and building records in the ICT system created by the use of the results of surveying works in the process of the modernisation of land records and registers and buildings, files and a cadastral map created on the basis of the database;
– a file of documents justifying entries in the database (Act 1989, article 24).

The information contained in the database is public and may be made available in the form of an extract from the register, an excerpt from a cadastral map, copies of documents, computer files, and services. They are available to the owner, public administration authorities and anyone who demonstrates a legal interest in this regard (Act 1989, Article 24).

The documentation of land and building records is updated *ex officio* or at the request of the owner. These persons are obliged to report this documentation to a competent district head within 30 days from the date of the change in the data included in the Register of Land and Buildings (Act 1989, art. 22 and art. 24).

Within the scope of the LMR register, on request and for a fee, you can obtain an excerpt from the Land and Mortgage Register, as well as an excerpt from the files (Act 1982 art. 36[4]). In addition, if you know the number of the land and mortgage register, it is possible to obtain access to a full excerpt through the portal of the Electronic Land Registers, https://ekw.ms.gov.pl/, made available by the Ministry of Justice.

Data from land and building records are available for review via the Polish geoportal www.geoportal.gov.pl (Figure 6). Until 2020, the scope of data made available in the geoportal included the number of the land and mortgage register. This information is currently unavailable.

6 COMPARATIVE ANALYSIS OF THE REAL ESTATE CADASTRES IN SLOVAKIA AND POLAND

The comparative analysis conducted was based on 14 issues characterising a cadastral system. The aspects distinguished were assessed in terms of analogy or differentiation in both countries. This analysis focuses primarily on the real estate aspects. The results of the comparison are presented in Table 1.

7 CONCLUSIONS

An analysis of the table shows that the principles of the cadastre functioning in Poland and Slovakia are similar, to some degree.

The main difference between the two is due to the nature of the cadastral systems in Poland and Slovakia. Slovakia has a full-fledged real estate cadastre that combines cadastral information, a cadastral map, and a register of rights to land, buildings and premises. In Poland, on the other hand, two databases are used for the cadastre, i.e., land and building records that provide descriptive and graphic information about land, buildings and premises, and land and mortgage registers containing information on rights to land, buildings and premises. These registers are kept by two separate institutions. There is also a greater range of entities entered into the system with rights to real estate. There is also a difference in the content of the cadastral documentation, which in Slovakia is more extensive in relation to the content of the legal data.

Note also the difference in defining the primary cadastre structure, i.e., real estate. In Poland, the definition of real

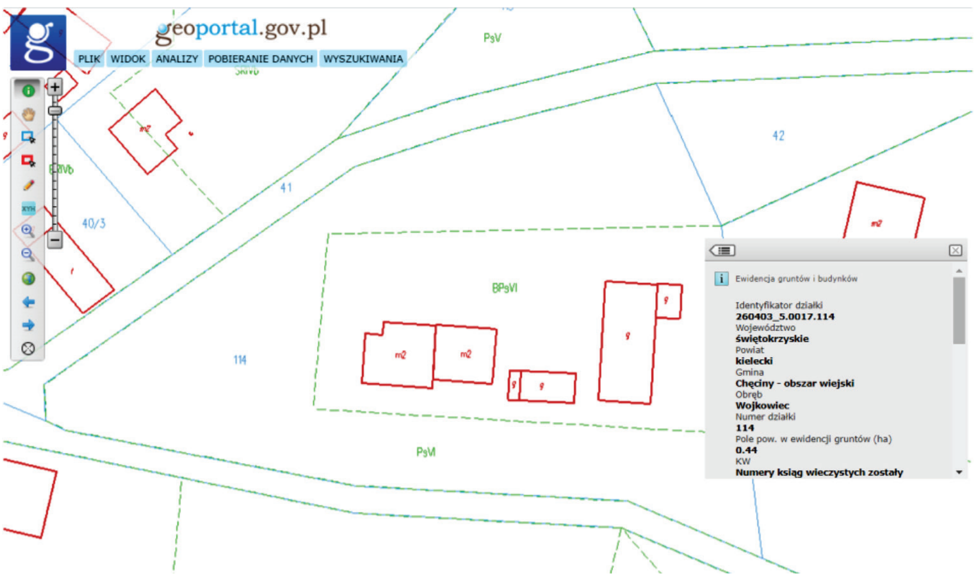

Fig. 6 *Fragment of the Polish geoportal.* Source: *https://mapy.geoportal.gov.pl/*

Tab. 1 *Comparison of the cadastral systems in Poland and Slovakia according to the established criteria.*

Category	**Poland**	**Slovakia**	**comparison**
Cadastre definition	The land and building register is an information system ensuring the collection, updating and sharing, in a uniform manner for the country, information on land, buildings and premises, their owners and other entities that own or manage these land, buildings or premises. Land registers provide information on the rights of various entities to real estate.	The real estate cadastre is a geometric designation, inventory and description of real estate together with data on the rights to this real estate.	difference
General rules	The data is open, common, and up-to-date	The data is open, common, and up-to-date	analogy
Cadastral map	The Land and Property Register map - a large-scale cartographic study containing information on the spatial location of cadastral plots, buildings, contours of land use, classification outlines and descriptive information on these objects. It is part of a basic map for the entire country.	Cadastral Map - a large-scale planimetric map showing all real estate and cadastral areas registered in the cadastre. The lands are represented on the map by projecting their boundaries onto the projection plane and are identified by plot numbers and, as a rule, by the type of land.	analogy
The form of a cadastral map	numeric	numeric and analogue	difference
Lead authority	District starost (or mayor of a city with district rights)	Central body - The Geodesy, Cartography and Cadastre Authority of the Slovak Republic District authorities - district offices	analogy
Cadastral division units	− registration unit, − registration area, − registration plot	− cadastral district, − cadastral plot	difference
Cadastre Objects	LPR - registration plot, building, premises LMR - real estate of land, real estate for buildings and premises	Real estate: plot, building, building under construction, residential unit, residential unit under construction, non-residential unit, non-residential unit under construction.	difference
Property	Real estate is a part of the land constituting a separate subject of ownership (land), as well as buildings permanently connected with the land or parts of such buildings; if under special provisions, they constitute an object of ownership separate from the land.	Real estate is land and buildings connected to the land with a solid foundation, including underground structures.	difference
Cadastral entities	− Owner / co-owner − Perpetual usufructuary / perpetual co-user − Independent holder / joint holder	− Owner / co-owner − Pledgee, − Beneficiary of the right of pre-emption, − Beneficiary of the easement, − Tenant − Manager of state or communal property − Slovak Land Fund and forest land manager	difference
Composition of the cadastral documentation	− database of land and building records in the ICT system − file of documents	− file of survey data - cadastral map, − a set of descriptive information about cadastral objects, rights to them, owners and other entitled persons, and data from the ownership deed, − a set of documents constituting the basis for an entry in the cadastre, − summary of data on the Land Fund, − land and mortgage registers, railway registers and their datasheets serving as a source of catastral data.	difference
Register of property rights	The Property Rights Register is the Land and Mortgage Register (LMR), separate from the Land and Building Register (LPR).	The Register of Property Rights is part of the cadastral documentation.	difference
Types of boundaries	Efforts are made to establish the boundaries determined according to the legal status, but there are still boundaries determined according to the actual state on the ground.	The border may be territorial, a cadastral area, or a built-up area, determined by the right to the real estate, ownership, type of land, method of use	difference

Category	Poland	Slovakia	comparison
Types of land use	− agricultural land (arable land, permanent meadows, permanent pastures, orchards, built-up agricultural land, wooded and shrubby land on agricultural soil, land under ponds, land under ditches, wasteland), − forest, wooded and bushy land − built-up and urbanised land − land under water − miscellaneous areas.	− arable land, − growing hops, − vineyards, − gardens, − fruit orchards, − permanent grassland, − forest land, − water areas, − built-up areas and courtyards, − other areas.	analogy
Extracts and extracts from the cadastre	In electronic or paper version, to anyone with a legal interest	In electronic or paper version, the owner or other authorised person	analogy

Source: *authors' study based on Act 1989, Act 1995, Regulation 2009, Regulation 2021*

estate includes a building erected on land, while in Slovakia, the building becomes a separate real estate entity. Moreover, the area and the plot are understood differently, and thus the type of borders registered in the cadastre are also different. The difference also appears in the territorial divisions of the country. In Poland, this division has more grades, which may result from the larger area of this country.

Another significant difference concerns the cadastral map: in Slovakia, analogue maps are still in force and on a par with numerical maps, while in Poland, the maps are fully digital. However, the contents of the maps in both countries are similar.

In terms of similarities in both countries, the principle of universality applies, i.e., the cadastre operates for the entire territory of the country; as to the principle of credibility, entry is made on the basis of relevant documents, and as to the principle of openness, cadastral data is made available on request or via internet portals. Moreover, the types of land use are similarly distinguished in both countries compared.

A comparison of the cadastral systems operating in the neighbouring countries of Slovakia and Poland shows how much difference there is between the systems, which derive from one historic Austrio-Hungarian cadastre. Neither systems is not perfect, but Slovakia has a cadastre in the full sense, while Poland is still striving to transform the existing registers into a fully-fledged cadastre.

In terms of the aspirations of European countries to unify their cadastral systems, Slovakia seems to be in a better position because of its organised cadastre that can be converted to the new European guidelines. Poland, on the other hand, has a system that is entirely based on ICT solutions, which can speed up data integration and transformation of the existing system.

The comparison carried out raises a number of further significant issues that could be compared and analysed in particular for the purpose of concretising the idea of a common cadastre for many countries.

Expanding the knowledge of cadastral solutions allows for a broader view and a comparison of situation in one's own country. The exchange of experiences is one of the most important aspects of the pursuit of development and transformation in every aspect related to real estate management, especially with regard to the desired state of integration of the land register and the legal register in the cadastral system.

8 SUMMARY

Slovakia and Poland share some common cadastral history, but after World War II, the development of the two systems took different paths. Both countries are currently bound by EU regulations and international standards that aim to standardise the cadastral systems all over the world.

This article attempts to compare the general principles of the functioning of the cadastre in both countries. The results obtained show that both countries can draw inspiration from each other to improve their systems and adapt to international standards. Digitization of cadastral maps is important for Slovakia. For Poland, the most important goal is to create a fully fledged cadastre by harmonising and integrating existing databases and defining a uniform subject of the basic cadastre, which should be real estate.

Acknowledgements

This article was created as part of the international cooperation between the Department of Geodesy at the University of Agriculture in Cracow (Poland) and the Department of Geodesy at the Slovak University of Technology in Bratislava (Slovakia).

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sciendo
Slovak Journal
of Civil Engineering
Vol. 31, 2023, No. 1, 10 – 21
DOI: 10.2478/sjce-2023-0002

HARDENING ACCELERATORS (X-SEED 100 BASF, PCC, LKD AND SALT) AS STRENGTH-ENHANCING ADMIXTURE SOLUTIONS FOR SOIL STABILIZATION

Per LINDH[1,2*], Polina LEMENKOVA[3**]

Abstract

This study is aimed at evaluating the strength of stabilised soil collected from the Port of Norvik, Stockholm, Sweden, where 350,000 m³ of clay had to be stabilized. The tests were performed in the laboratory of the Swedish Geotechnical Institute (SGI). The soil was stabilised by binder mixtures using Portland cement clinker (PCC) and lime and lime kiln dust (LKD). Accelerators (X-seed 100 BASF, PCC, LKD and salt) were added to the soil samples for quicker stabilization. The strength of the stabilised soil was assessed using resonance frequency measurements of seismic P-waves by an ICP accelerometer in order to estimate the shear strength of the soil and to evaluate the effects from the accelerators, binder ratios, and the curing temperature on the gains in stabilization and strength. Various proportions of the binders were tested, i.e.: 50/50 cement/lime and 50/50 PCC/lime. The temperature was measured using a calorimeter in double experiments. The results showed that the accelerators improve the strength in the stabilized specimens and enhance the soil performance for engineering construction work.

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Key words

- Accelerator,
- X-seed 100,
- Lime kiln dust,
- Construction materials,
- Geotechnical engineering,
- Resonance frequency,
- P-waves,
- Structural mechanics,
- Engineering geology.

1 INTRODUCTION

Fine-grained cohesive soil should be stabilised before its use in construction work (Dahlin et al., 1999; She et al., 2019; Lindh, 2004; Zhou et al., 2017; Lemenkov and Lemenkova, 2021a). Stabilisation improves the engineering properties of fine-grained soil by increasing its compressive strength (Brencich et al., 2021; Lemenkov and Lemenkova, 2021b; Wu et al., 2021), reducing its plasticity (Kasprzhitskii et al., 2016) and shrink-swell potential (Chen et al., 2002; Saride et al., 2013), and improving its mineralogical, morphological and structural characteristics (James, 2020; Wang et al., 2021). These improvements result in a higher bearing capacity, reduced settlement, and more predictable behavior of the problematic soil.

Various methods are employed to achieve more stable soil. They include mechanical and chemical approaches, as reported in previous studies (Koukouzas et al., 2022; Lindh et al., 2000; Källén et al., 2014, 2016; Lindh and Lemenkova, 2021a). The chemical stabilization of clayey soils is usually a complex hydration process involving reactions between the additive and clay-water systems within the soil structure (Patel, 2019). The success of soil stabilization strongly depends on a variety of factors, i.e., the physiochemical properties of the soil (Zhang et al., 2022); the water-binder ratio (Wang et al., 2022a); the mixing efforts; the curing conditions; the temperature and the duration of the solidification (Lindh and Winter, 2003); the hydration mechanism of the binders (Scrivener et al., 2015); the effect of the accelerators added to the binder; and the organic and foreign inclusions or contaminants in the original soil structure; e.g., clay, silt and fine-grained or coarse-grained types of soil (Lindh, 2003; Akomah et al., 2021). Therefore, the final effect on the setting of the soil mixture may vary during the stabilization process.

Binders can either include traditional or novel materials. Cement is the oldest and most recognized soil binder (Buritatum et al., 2021) due to its effectiveness; it is the primary hydraulic binder for soil (Young, 2001). However, to improve its speed and effectiveness, other binders may be included as well. For instance, lime, polymer-based binders, industrial by-products or cementitious materials, such as fly ash or cement kiln dust, may be combined with cement. Various combinations of the binders are then tested in a laboratory to determine the most effective and economic solution (Khabiri and Ebrahimialavijeh, 2021; Lindh 2001).

The search for effective methods of rapid soil stabilization is one of the fundamental tasks in the construction industry and particularly in civil engineering. The question of rapid soil stabilization arises with larger treatment quantities (hundreds of tons). Adding accelerators to traditional binders for soil stabilization has recently attracted much attention in civil engineering and the construction industry (Meng et al., 2017; Luo et al., 2021; Kantesaria et al., 2021; Zhang et al., 2021; Zhao and Khoshnazar, 2021; Wang et al., 2022b). Combinations of admixtures significantly improve the physical and mechanical properties of clayey soil. Accelerators can be used as catalysts to reduce reaction times, which lead to higher early strengths, rapid hydration, and the improved microstructure of cement as a binder for soil stabilization. Adding catalysts as admixtures may also increase the compressive strength of the materials (Yang et al., 2021).

Quantifying the degree of soil improvement requires field and laboratory testing. Measuring the soil's strength (undrained or drained), stiffness (modulus), and density are typical approaches. A more recent method measures the vibratory resonance frequency of a laboratory specimen to evaluate the stiffness and strength of the stabilised soil (Mamoon and Ahmad, 1990; Coe and Brandenberg, 2010; Verástegui-Flores et al., 2015; Lindh and Lemenkova, 2021b). A seismic testing procedure has been developed by the Swedish Institute of Standards (SIS, 2019) and applied for practical use in the Swedish Geotechnical Institute (SGI).

In this paper we have evaluated the effects of adding accelerators to soil stabilised with binder mixtures of Portland cement clinker (PCC), lime, and lime kiln dust (LKD). Various accelerators (X-seed 100 BASF, PCC, LKD and salt) were added, and their effect on the soil stabilization was assessed using the P-wave resonance (stiffness) of the laboratory specimens. The measurements were then correlated with laboratory strength tests.

2 FORMULATION OF THE PROBLEM

Traditionally, specimens of stabilized soil have been compacted in piston sampling sleeves with a diameter of 50 mm and a length of 170 mm (i.e., 5×17 cm). In an external assignment at the Port of Norvik, Stockholm, where 350,000 m^3 of clay was to be stabilized, we were given the opportunity to conduct statistical experiments in an empirical study in order to evaluate the effectiveness of new and untested binders. A traditional approach could be to test only a single combination of binders, while varying the percentage of the binder added to the soil. However, by altering the composition of the binder itself as well as varying the percentage added to the soil, we were able to evaluate a broader variety of possible design solutions. Of course, this required a much larger number of tests to establish a meaningful data set for the statistical tests.

The main approach of this study was to use our laboratory's geophysical equipment and the resonant frequency method to quantify the improvement of the soil due to various additives. In the traditional packaging of the test sleeves, they are filled to about an 80 % volume with the stabilized soil and leaving a portion of the sleeve empty. However, during the experiments with the resonance frequency measurements (P-wave), it was found that the empty part of the sleeve gave a resonance frequency that hides the resonance frequency of the specimen itself. This could bias the experimental results. Furthermore, there was a problem with the packed surface not being flat, which also disturbed the measurements. Therefore, the solution to these problems was to fill the test specimens completely with the material, which is similar to the procedure for surface stabilization. There are two options to achieve this goal: 1) fill in the standard sleeves completely; 2) make shorter sleeves that are trimmed (smoothed) immediately after packing and before the curing soil. We selected the latter technique.

Resonance frequency measurements were demonstrated to be a useful geophysical technique that provides a high degree of repeatability due to its non-destructive nature. It enables comparing samples stored at different temperatures and obtaining a correct K-factor for calculating maturity numbers (Åhnberg and Holm, 1987). Introducing the maturity number with regard to the development of P-wave velocity enabled the calculation of the maturity and strength of the soil specimens. In combination with the experimental results of the P-waves, the maturity number enables evaluating and assessing the shear strength and UCS development of the stabilized soil. It can be effectively used when measuring P-waves to integrate field measurements with laboratory experiments. However, more research is needed to understand the effect of the stress level on curing the soil. A simple calorimeter measurement has been shown to be a fast and cheap method to check the reactivity of different binders and their combinations with accelerators by evaluating the temperature developments in the binder mixture. This method has a very high degree of repeatability using the existing description and approach.

In connection with this method, questions have arisen as to how such binding agents as accelerators could affect the increase in the strength of the stabilized soil. Due to the fact that alternative binders are not as reactive as lime and cement, they produce a slower increase in soil strength. Slower increases of soil strength are likely to have a negative impact on civil engineering projects, especially those connected with construction works, e.g., roads or buildings. Furthermore, there have been considerations as to whether the accelerators would reduce leaching from any contaminated sediments. This is important since early gel formation and curing is desirable to prevent the early leaching of stabilized sediments. The focus of the study is to improve the techniques for testing soil specimens stabilised with binders to improve the bearing capacity of soil. The soil specimens included samples of marine sediments dredged from the Port of Norvik in Stockholm.

The study investigated whether it is possible to fabricate a test specimen in a new, more time-efficient way that could be stored in a sleeve and used for strength estimates by resonance frequency measurements during the storage period. The objective of the study is to improve and adapt packaging equipment for a non-destructive testing of soil strength using geophysical methods of P-waves in such a way that testing can take place during the entire curing process of the samples. The aims of the study were: a) to determine the effects of accelerators on the speed of soil stabilization; b) to test how the storage temperature affects the increase in soil strength; c) to verify that the intended method performs well and can be applied as an effective production method for soil sampling and the measuring of the strength of the stabilized specimens; and d) to estimate the effects of using accelerators and different curing temperatures.

3 METHODOLOGY

Three different tasks have been evaluated in the project: i) adding binders with the subsequent packaging of soil samples; ii) resonance frequency measurements of the soil using P-waves aimed at measuring the natural frequencies of the vibrations in the tested specimen to indicate the soil strength; iii) a simplified calorimeter measurement of the reactivity of the binders used for soil stabilization.

3.1 Mixing and packing of soil samples

The mixing experiments involved an initial homogenization of the soil aimed at building a uniform cylindrical soil column with a sample. The specimens used in this study included fine-grained ML-silt types according to ASTM. These include inorganic silts, very fine sand, rock flour, silty or clayey fine sands, and clayey silts with a slight degree of plasticity (index <4). Such soil types exhibit little or no strength when air dried, according to the ASTM D2487-06, Unified Soil Classification System (Howard, 1986). The particle size distribution (grading) of the soil samples was determined according to the Swedish standard SS-EN ISO 17892-4:2016 (SIS, 2016) with a maximum <20 mm diameter of the larger element particles. Most of the grain size particles were less than 0.06 mm, i.e., the mechanical behavior of the soil was affected by its fine fractions. The mineralogical identification of the specimens shown in addition to the silt (grain size <0.063 mm) also included the occasional occurrence of well-graded sands and gravelly sands (SW), poorly graded sands (SP), and silty sands (SM) (grain size 0.063-2 mm). Sometimes, silty gravels as well as gravel-sand-silt mixtures were found (GM) and clayey gravels with gravel-sand clays (GC). The specimens also very rarely had inclusions of well-graded gravels, gravel-sand mixtures (GW), and poorly-graded gravels and gravel-sand (GP) (2-8 mm grain size diameters).

The dry specimens were thoroughly mixed with distilled water in a mixing bowl by a large mixer for 5 minutes. Water was added during the mixing process, and the samples were further mixed continuously until the consistency limits and linear

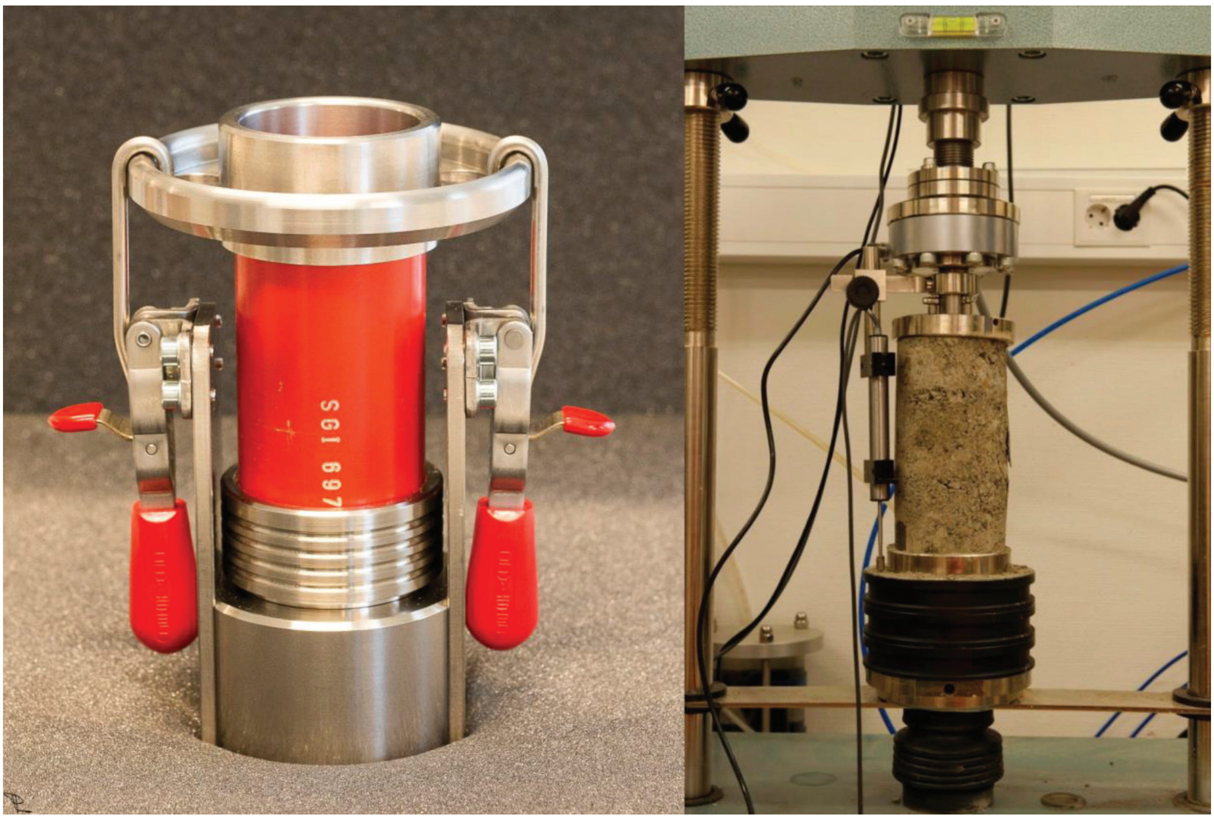

Fig. 1 *Left: Photo showing packaging equipment for packing specimens with a height of 100 mm. Right: UCS testing apparatus showing a specimen after the UCS test. Photo source: Per Lindh*

shrinkage were achieved. Afterwards, the binder blends and accelerators were added to these samples in different proportions (cement, lime, LKD, X-seed 100 and salt) and mixed with the soil for 5 minutes for homogenization. Immediately after mixing, the soil was packed into sampling sleeves, i.e., into plastic containers, which had a diameter/height of 5×17 cm. The specimens were packed in long sleeves and short sleeves with similar densities of the samples. The trimming of the sleeves after packing and before curing demonstrated their effectiveness. During the placement of the specimens, the sleeve was shaken on the table to loosen the air pores and ensure the even distribution of the soil. The optimal water ratio was determined based on the dry density of the soil using the SIS standard (SIS, 2003) as a volume fraction on the basis of the ratio of the measured water content mass to the known dry bulk density material. The amount and combination of the binder were determined before mixing based on the various percentages by weight.

Ordinary sampling sleeves with a height of 170 mm were used where the sleeve was manually packed in layers up to ca. 150 mm. The soil samples were trimmed to 100 mm to produce an L/D ratio of the specimen as 1/2, so that the end effects did not dominate the compressive behavior. In the traditional methods, the samples are usually packed directly into the sleeves without any holders. In this study, we applied the modified variants with 100 mm long sleeves. Fig. 1 (left) shows the equipment used for the study, which included a cylindrical mould with a bracket to hold it down to the base. The UCS tests were carried out in a 10-ton testing apparatus, Fig. 1 (right). The tests were run for the deformation control of the soil samples according to the SS-EN 13286-41 standard with a breaking load reached within one minute and a deformation rate of 3 to 4 mm/s.

3.2 Resonance frequency measurements by P-waves

The strength of the stabilized soil was evaluated using the non-destructive method of measuring the P-wave velocities, based on the theory of waves and the geophysical properties of soil as a porous media. The advantages of using P-waves for testing the physical properties of soil is that they are sensitive to the material's structure and travel through all kinds of media, including porous and solid structures, liquids and gases. Moreover, among the other elastic seismic waves, i.e., Rayleigh, Love, shear (S), and compression (P), P-waves have the greatest velocity, which is convenient for measuring material properties. Seismic P-waves transmit energy by the vibration of the soil particles, which vibrate in the direction of the wave propagation.

The seismic tests included measurements of the velocity of the P-waves propagating through the soil. A comparison of the different specimens enabled assessing the gains in soil strength obtained through the addition of binders. The core idea is that the values of the P-wave velocity correlate with the strength of the soil. Seismic measurements were performed using the proprietary software of the Swedish Geotechnical Institute (SGI). The equipment for the P-wave measurements included the lightweight ceramic shear response (ICP) Accelerometer (PCB Piezotronics Group Inc. (2013). The resonance frequency measurement was performed using a vibration source and vibration receiver in the ICP Accelerometer. The receiver was connected to a computer for data collection (Figs. 2 and 3). The P-wave velocity was measured

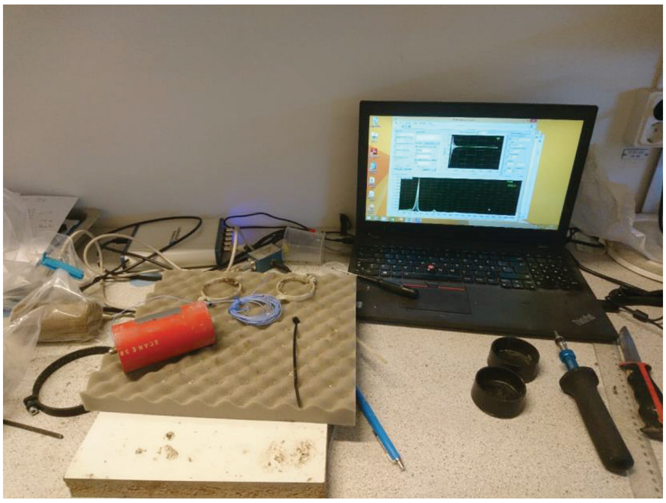

Fig. 2 *Setup of seismic experiments for measuring P-wave velocity. Photo: Per Lindh*

using a standard device setting with a frequency range of 2 to 10000 Hz (±5%).

The procedure included the following workflow: The soil specimens tested in the cylindrical form were placed on a foam rubber pad substrate in order to vibrate freely. An impulse force was excited in the specimens with a transient impulse source (Impact Resonance Testing) through oscillation by a hammer force. The vibrations in the samples were detected by the ICP Accelerometer attached to the specimens. The vibrations were measured as a function of the time of the P-wave velocity propagation through the specimens. The data were recorded and transformed to the resonance frequency (Hz) via a software program (see Fig. 3, which illustrates the process).

The receiver was adjusted on one end of the sample. An impulse force was excited by the hammer at the other end of the sample. The arrival time was used to estimate the P-wave travel time. The velocity of the P-wave was calculated from the travel time of the pulse of the wave propagating through the specimens. The data on the P-wave velocities were recorded in the computer. The post-processing of the data on the P-wave velocity measured on the specimens was based on a methodology developed by SIS using 'Free-free resonance column' software developed at SGI by Martin Holmen, Fig. 3.

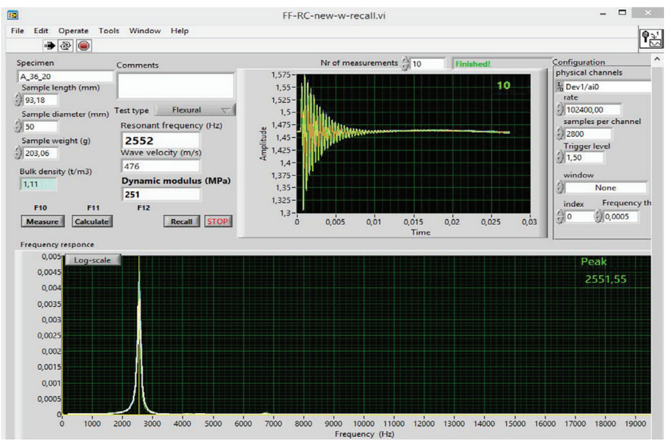

Fig. 3 *Seismic program testing the bend mode on a stabilized soil specimen*

The P-wave velocity was estimated as V = L/t, where V = velocity (m/s), L = sample length (m) and T = travel time (s) which was adapted from previous works (Ismail and Ryden, 2014). The P-wave velocity of the indicated strength of the soil specimens was stabilised by different binders. The P-wave velocities (Vp-value) increased with the curing time and with the percentage of the cementitious binder. The speed of the compression P-waves was measured in the specimens for the whole period on days 28 (Fig. 7), 50 (Fig. 8), 41 (Fig. 9 and 10) and 100 (Fig. 11). There are three fundamental oscillation modes for the cylindrical test body. These included: 1) the axial 2) bending and 3) torsional modes. The axial oscillation mode generates a compression wave (primary wave, P-wave). The torsion mode generates secondary waves and S-waves. P and S-waves are those waves that are primarily used in surface wave seismic tests, as well as in crosshole and downhole seismic tests. These were used to measure the shear and P-wave velocity profiles of the soil according to the standards (SIS, 2019).

Fig. 4 *Photo showing a simplified calorimeter consisting of a thermos and a temperature logger. Photo source: Per Lindh*

The S-wave has an advantage in that it is not significantly affected by the degree of the water saturation of the material. The P-wave, on the other hand, is greatly affected by the degree of water saturation. In an unsaturated sample body, the P-wave measurement gives the P-wave velocity of the material, while in a water-saturated sample body, water contributes to an increase of the speed of the P-wave evaluated. This is caused by the geophysical properties of P-waves: the P-wave velocity of water is usually greater than the P-wave velocity of a solid soil body. This phenomenon can be used to determine whether a specimen is saturated with water or not.

The bend mode generates a wave, which can be described simply as a combination of S and P-waves. This wave is very easy to excite and usually gives the best signal, see Fig. 2, which results in its wide application in seismic experiments. Similar approaches have been applied in earlier works, e.g., longitudinal resonance tests (Drnevich and Ashlock, 2017), torsional resonance tests (Lo Presti et al., 1997, 2007; Drnevich et al., 1987; Isenhower et al., 1987), resonance column tests (Vrettos and Banzibaganye, 2022); and bender element tests. Besides, some cases report the incorrect calculation of the shear wave from the bending wave measurements (Verástegui-Flores, 2015). Therefore, the use of the bending mode to calculate the shear wave velocity gives an overestimation of its value. The plots showing the results and demonstrating the P-wave velocity developed over the curing time are given in Figs. 7–11. The seismic velocities were measured as a function of the curing time to evaluate the strength development in the stabilized soil.

3.3 Simplified calorimeter

The simplified calorimeter consisted of a steel thermos equipped with a thermometer, Fig. 4. The variations in the temperature of the binder slurry (water, binder and accelerants) were measured in the thermos. Here, the ratio between the weight of the water and the weight of the binder was 1.0. A WBR of 1.0 means an equal weight of water and binder, i.e., the water/binder ratio is 1:1. The water used in the experiments was at room temperature. The experiment compared the exothermic properties of the different mixtures. The difference in the heat capacity between the binders could be calculated. However, the method has been developed for a direct comparison of the temperatures.

4 RESULTS

4.1 Mixing and packing of soil in short sleeves

The increased P-wave velocity of the soil samples is associated with the increased strength of soil stabilized with binders. In this experiment we employed three different binders, i.e., as cement, lime, LKD, and X-seed 100 accelerators to test the effect of the stabilizer contents on the improved properties of the soil tested by seismic tests. Three different types of binder mixtures were tested as shown in Tab. 1. One can see that Case No. 1 was based on a mixture of the soil with a cement/lime/LKD blend; Case No. 2 – with cement/lime binders and the accelerator X-seed 100, and Case No. 3 with cement/lime and salt.

Tab. 1. *Stabilizing agents (binders and accelerators) included as the components to the soil mixture in Cases Nos. 1, 2 and 3.*

Case	Cement	Lime	LKD	X-seed 100	Salt
1	x	x	x	–	–
2	x	x	–	x	–
3	x	x	–	–	x

The first binder mixture used cement, lime and lime kiln dust (LKD). LKD is not a standardized product, which is why the chemical composition has greater variations compared to the traditional binders. The second binder mixture consisted of cement, lime, and accelerator X-seed 100, BASF. The X-Seed 100 was developed by BASF Technology Center in Trostberg/Germany (TBA Trimmiser Baustoffe AG, 2010). This technology is based on an injection of the pore solution of the cement with synthetically manufactured calcium-silicate-hydrate crystallites as liquid admixtures (TBA Trimmiser Baustoffe AG 2010). The X-Seed 100 accelerator is an effective strength-enhancing admixture solution, which notably improves the development of strength in the Portland cement used in the construction industry and for soil stabilization. The third binder mixture contained cement, lime and salt.

The percentage of the admixture of X-seed 100 for each of the three cases was 2.5%, 5% and 7.5%, respectively, which was defined based on the amount of the binder. Adding the X-Seed 100 as an accelerator enabled the promotion of better soil hardening at room temperature, which contributed to the stabilization of the soil. In the third mixture, cement, lime and salt were used as accelerators and demonstrated the development of strength in the soil samples stabilized by the binders in proportions of 40/60%, 50/50% and 25/75% of the cement/lime and 40/40/20% of the cement/lime/salt combination. For the samples stabilized with salt, 20,10 and 55% weight percentages (%) of salt were used for Case No. 3, based on the amount of the binder. The combination of binders and accelerators totals 100%, see Table 2. However, the results show no significant difference between the samples stabilized with or without salt, see Figs. 9 and 10 for a comparison. The mean and standard deviations of the packed samples were calculated to verify the quality of the packaging, Fig. 5. The components of the binders and accelerators were mixed together with different ratios in mixtures, Tab. 2.

Tab. 2. *Mixtures of the proportions of stabilizing agents (binders and accelerators) in Cases Nos. 1, 2 and 3 and the samples a, b and c tested.*

Case	Binders		Accelerators		
	Cement	Lime	LKD	X-seed 100	Salt
1a,b,c	60,40,40	40,40,30	0,20,30	–	–
2a,b,c	60,50,40	37.5,45,52,5	–	2.5,5.0,7.5	–
3a,b,c	40,50,25	40,40,20	–	–	20,10,55

To compare the present results with those from the experiments on the packaging traditionally used, a compilation was made from a previous study (Norvik), where the specimens were packed in a 170 mm sleeve and then trimmed down to a 100 mm sleeve in connection with the routine testing. The soil density was estimated according to the existing methods of the Swedish Institute of Standards (SIS, 2017a) using the trimmed specimens.

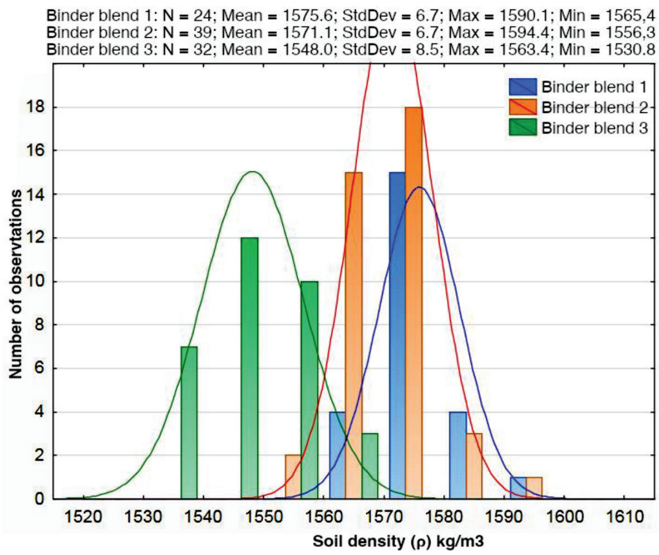

Fig. 5 *Density of the soil specimens packed in short sleeves.*

A statistical summary is presented in Fig. 6 with the standard deviation varying between 10.8 and 12.9. The colours on the graph in Fig. 6 correspond to the amounts of the binder blends (binder and soil) in kg, as follows: the blue is for Blend No. 1, which has 80 kg, the orange stands for 100 kg of Blend No. 2 and the green stands for Blend No. 3 (120 kg of materials). The results indicate the slightly higher values of the mean and smaller standard deviations, according to the new method. However, future studies should include a t-test designed with the zero hypothesis that there is no difference between the methods.

The most probable explanation for the differences between the two methods is that there is less friction in a cylindrical soil column when packing according to the new method, which gives a higher degree of packing, fewer deformities, and thus a higher density of the soil samples.

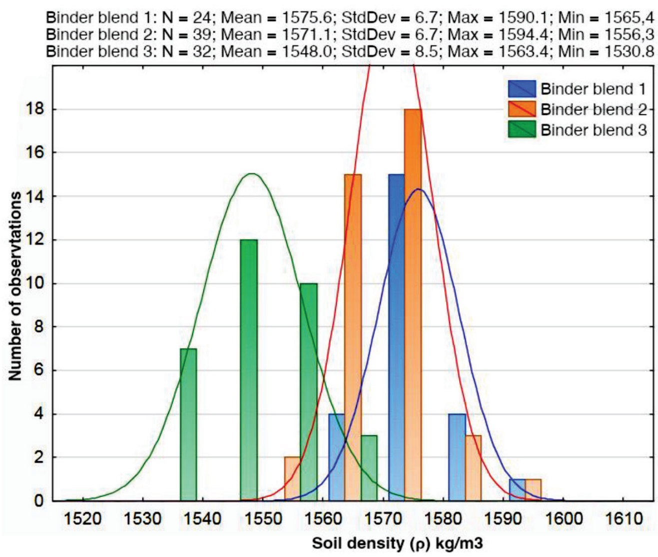

Fig. 6 *Density of the specimens packed in long-sleeves (standard procedure).*

4.2 Results of the resonance frequency measurements

In the experiment, UCS testing was performed on all the soil specimens using Swedish standard SS-17892-7:2017 (SIS, 2017b). Each specimen was loaded until the peak stress was obtained. The tests included the addition of various percentages of binders (cement/lime/LKD, and X-seed 100 and salt accelerators) to the specimens. The specimens were treated for different curing periods, i.e., a total of over 3 months (28, 41, 50 and 100 days); they were then extracted from the sleeves, subjected to UCS testing, and tested by the P-waves.

Fig. 7 shows the results of the P-wave velocities tested on the stabilized specimens by 20 °C from Day 1 to 28. The indices of the curves include the temperature and the number of the sample. Thus, *T20_x* means a storage temperature of 20°C and that it is Sample No. X. Index A indicates that the sample contains an accelerator. From Fig. 7 we can conclude that the P-wave velocity increased from the initial speed of 450 m/s until 750 m/s in 7 days of curing in the five soil-binder mixture specimens tested with the addition of accelerators X-seed and salt, after which the P-wave speed stabilized, increased slightly, and reached a maximum of 900 m/s on Day 28 of the curing period.

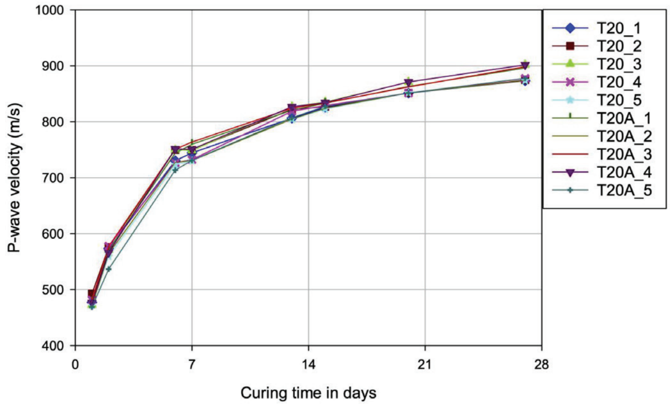

Fig. 7 *P-wave velocity as a function of the storage time at 20 °C.*

The evaluation of the accelerators (X-seed 100 and salt) using the P-wave velocity did not indicate a significant difference in the curing process either at a curing temperature of 7°C or at a temperature of 20°C, see Figs. 7 and 8 for a comparison. From Fig. 8 we can also see that the speed of the P-waves correlates well to the curing time for several of the single specimens stabilized with binders and accelerators. Thus, Fig. 8 displays the speed-ups for the P-wave velocities from Day 7 to Day 50 owing to the increase in strength in the specimens over the time of curing due to the accelerants added into the binder mixtures. Thus, compared to the results of previous studies on the measured strength of the fine-grained soil using traditional methods (Lindh, 2001, 2004), the addition of the accelerators increased the gain in strength in the soil specimens.

The curves in Fig. 8 correspond to the speed of the P-waves, which increased from 500 m/s to 780 m/s starting from Day 7 to 50 of the curing. Adding the accelerators to the cement, lime and LKD caused a maximum increase in the P-wave with the addition of 2.5%, 5% and 7.5% of the X-seed, respectively. It is worth noting that the velocity of the P-waves gained in speed during the initial curing period (days 1 to 7), after which it stabilized. We can further conclude that the speed-ups of the P-waves differed by the various temperatures. Thus, Fig. 7 shows the P-waves measured at a 20°T, while Fig. 8 is at 7°T. Comparing these two figures, one can see that the higher temperature (20°T) resulted in the increased speed of the P-wave. For instance, on day 14, the P-waves increased up to 820 m/s at 20°T (Fig. 7), while Fig. 8 shows that at 7°T, the measured P-wave velocities on the same day (14) did not exceed 620 m/s, which points at the effects from the temperature on the curing.

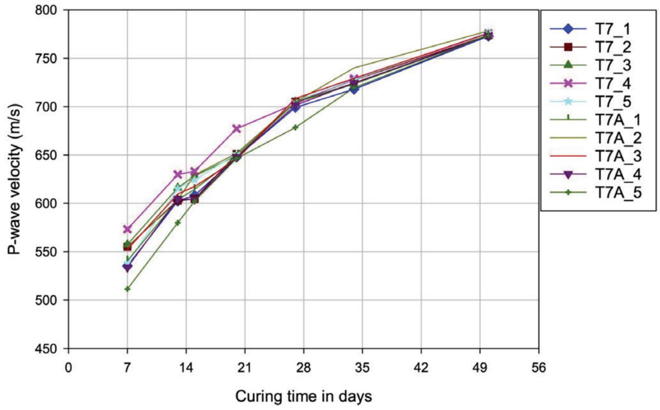

Fig. 8 *P-wave velocity as a function of curing time at 7 C°. T7_x means a storage temperature of 7 C° and Sample No. X. Index A means that sample includes an accelerator.*

Fig. 9 shows the results of the tests at 20°C. The indices of the curves signify the temperature and number of the sample. Thus, *BT_20_Sy_x* means curing T at 20 °C, and *Sy* indicates that the sample contains salt as an accelerator; x means the sample number. Index *y* varies from 1 to 4, where 1 indicates that the sample contains 1 % salt based on the amount of the binder. Fig 9 demonstrates that adding salt as an accelerator (in a content of 1 % with respect to the binder amount) increased the P-wave velocities up to 1050 m/s on day 41 by a curing temperature of 20°C.

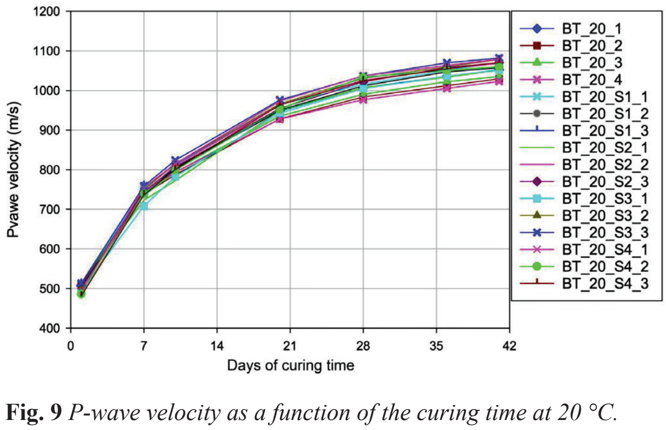

Fig. 9 *P-wave velocity as a function of the curing time at 20 °C.*

It also seems that the increase in speed is slightly more compared to Fig. 7, where the speed of the P-waves stabilized after day 21 at the same curing temperature. This indicates the positive contributions from the salt added as an accelerator on the continued gain in strength in the soil specimens. For the samples stabilized with salt as an accelerator, 1, 2, 3 and 4 %

by weight of the salt were used based on the amount of the binder. The results do not show any significant difference in the P-wave values between the samples with and without salt, see Figs. 9 and 10 for a comparison.

However, the performance of the gain in strength differs by the changed temperatures. Thus, Fig. 9 shows the tests performed at 20°C, while Fig. 10 shows tests performed at 20°C. Comparing these two graphs, we can see that the increase in P-wave speed (i.e., gain in strength) occurs more promptly and then stabilizes at 20°C, while it increases more moderately at 7°C, which indicates the external effects of the ambiance while testing the samples. Fig. 9 shows the increase in P-waves from 450 to 1400 for the samples stabilised with the added salt at T 20°C during the curing period from 1 to 41 days, while Fig. 10 shows the almost linear increase of the P-wave speed from 400 to 800 m/s for the period of Days 2 to 41 at T 7°C, where the lower parameters of the speed correspond to the lower temperature, respectively.

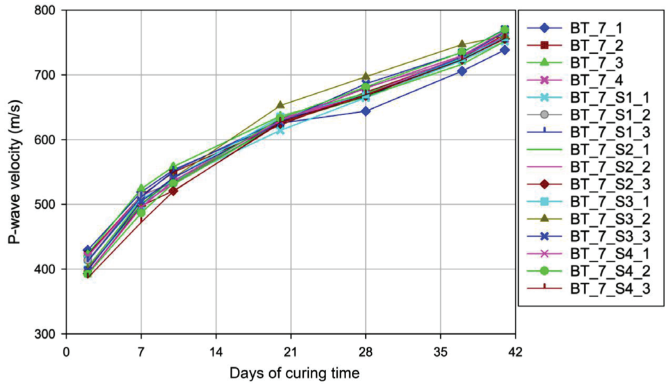

Fig. 10 *P-wave velocity as a function of storage time at 7 °C. BT_7_Sy_x means a storage temperature of 7 °C, and Sy indicates that the sample contains salt, while x means the sample number. Index y varies from 1 to 4, where 1 indicates that the sample contains 1% salt based on the amount of binder.*

However, adding various binders and accelerators contributes only slightly to the gain in strength, for example, in the case of Portland cement clinker (PCC) with a low gypsum content; a faster development of strength is obtained compared with a case of ordinary cement, see Fig. 11.

Fig. 11 shows the curves of the P-wave velocities versus the curing time (Days 1 to 100) for the six different cases of clay stabilized with 50/50 Portland cement type IIA / lime and 50/50 PCC / lime with added Portland cement clinker (PCC) with a low gypsum content. Comparing the cases of the added PCC and normal Portland cement, we can conclude that the final strengths achieved higher values by PCC, see Fig. 11 where the dots correspond to the added PCC, while the triangles denote cement as the binder. For example, the reduction in the curing time in these cases is calculated as follows: on day 21, the values with added Cem IIA/QI show the speed of the P-waves for sample 1 as 850 m/s, for sample 2 as 900 m/s, and for sample 3 as 865 m/s. In contrast, we can see that the added PCC increased the speed of the waves up to 970 and 980 m/s, respectively for the two different samples.

Likewise, on Day 42, the values with added Cem IIA/QI show the speed of the P-waves for sample 1 as 960 m/s, for sample 2 as 985 m/s, and for sample 3 as 940 m/s. In contrast, the added PCC increased the speed of the waves above 1000 m/s with values of 1030, 1040 and 1055 m/s, respectively, for the three different samples. This difference in the speed of 70 m/s continues and can be clearly seen as a distance gap between the batches of curves for the PCC-stabilized and cement-stabilised soil, respectively (Fig. 11). This illustrates certain benefits of the accelerators added to the binders for the soil hardening process.

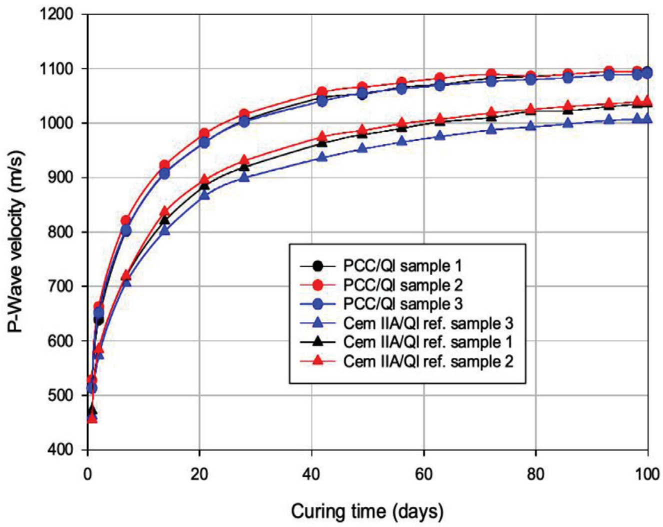

Fig. 11 *P-wave velocity as a function of the curing time for clay stabilized with 50/50 cement / lime and 50/50 PCC / lime. In the experiment, triple samplings were made for the statistical soundness of the test. Note the significant difference between the different groups.*

These effects can be explained by the properties of PCC, which contains a lower amount of gypsum. As a result, this gives a faster reaction compared to traditional cement, which can be clearly seen in Fig. 11. This faster reaction could be used to reduce processing time or to apply it in combination with a slow curing binder in order to obtain a satisfactory curing process.

The application of the resonance frequency measurements on the stabilized soil specimens is a proven technique with high repeatability due to its non-destructive nature (Barnaure et al., 2021; Dimter et al., 2016; Multon et al., 2022; Di Sante et al., 2022). Figs. 7 to 10 show the results from the P-wave measurements. The advantages of this method include the possibility of measuring the same soil specimen for a longer period of time without having affected its initial structure. This method can be used in this way to easily calculate the K-factor in the equation of the maturity number (M_T), using the existing formula, see below (Åhnberg and Holm, 1987).

$$M_T = [20 + (T - 20) * K]^2 * \sqrt{t}$$

where

T = temperature (°C)

t = time (days)

By storing specimens at different temperatures, e.g., 7 and 20 °C, see Fig. 12, the correct value of the M_T can be calculated, and a correct comparison between the different curing temperatures can be performed. For example, the M_T of soil treated at T 7°C (red line in Fig. 12) at the speed of P-waves of 400

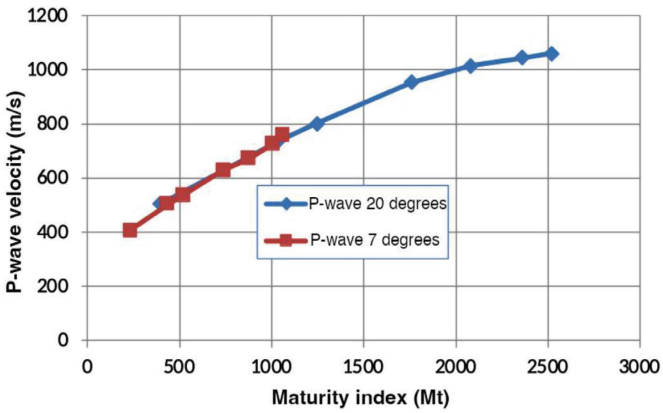

Fig. 12 *P-wave versus the maturity number for soil samples cured at different temperatures.*

m/s shows a value of 350 and then gradually increases in an almost linear way until 1100 by a P-wave velocity of 790 m/s with observations at T 7°C.

The M_T measured at T 20°C started at a P-wave speed of 550 m/s and coincided with those values at T 7°C; afterwards, the measurements continued with a similar correlation (the blue line in Fig. 12), showing, for instance, that the M_T 2000 is achieved by P-waves at 1000 m/s, after which the increase in M_T gradually stabilized and reached the maximal measured value of 2550 by P-waves at 1030 m/s, Fig. 12.

The geotechnical tests included testing the hardening process of the material, i.e., evaluating how much the strength developed after a certain number of days of curing at a certain temperature, which is of importance for both the geotechnical and environmental types of assessment. The testing strength was performed according to the Swedish standards for the uniaxial (unconfined) compressive strength (UCS) of soil (SIS, 2017b). The environmental assessment could also profit from the geophysical applications, which are of great importance in determining at what time leaching tests should be performed based on the curing time and temperature. A summary of how the shear strength relates to the P-wave velocity is presented in Fig. 13.

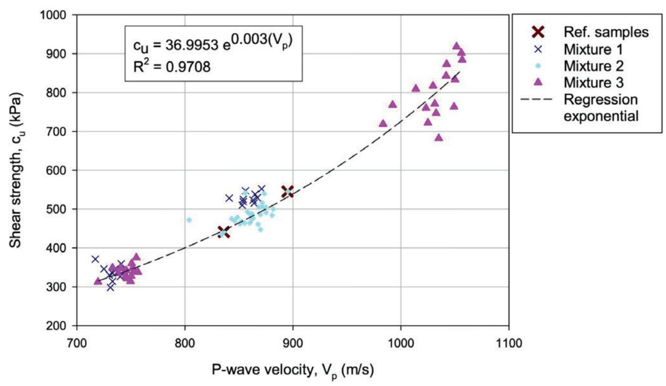

Fig. 13 *Graph showing the P-wave velocity as a function of the shear strength of the tested soil stabilized by various combinations of binders (Portland cement and lime) and accelerators. The accelerators include LKD in Mixture 1, X-seed 100 in Mixture 2 and salt in Mixture 3.*

As shown in Fig. 13, adding accelerators to the stabilized soil has an effect on the increase in shear strength and the corresponding increase in P-wave velocities. The results are generalized as an exponential curve with three major clusters of data that correspond to the groups of soil specimens tested. Here, the shear strength and P-wave velocity are evaluated for the three control groups of soil stabilized by the binders (Portland cement and lime) and accelerator (LKD in Mixture 1, X-seed 100 in Mixture 2, and salt in Mixture 3). Thus, Fig. 13 indicates that by adding the accelerators, the shear strength of the soil in the first group of measurements was estimated to be in a range between 300 to 380 kPa, with P-waves from 720 to 760 m/s. The speed of the P-waves increased slightly after the gain in strength, which corresponds to the P-waves at the interval between 830 and 890 m/s and the shear strength at 420–560 kPa (the second cluster in Fig. 13). The maximal P-waves are due to the strength developed during the curing time, which corresponds to the P-waves of 970–1060 m/s and the shear strength at the interval of 685-910 kPa (the third cluster in Fig. 13). In such a way, the maximal increase in strength will slightly increase by adding the X-seed and salt accelerators as the stabilizers to the soil (lime, LKD and cement), which is reflected in the P-wave speed.

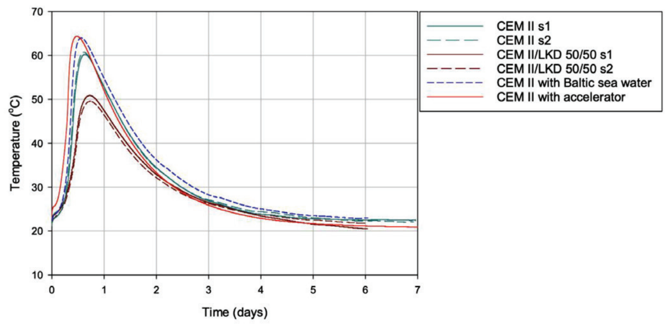

Fig. 14 *Temperature measurements for various binders and binder combinations*

4.3 Results of simple calorimeter measurements

The method of measuring the development of the temperature in a binder slurry using a simple calorimeter results in a high repeatability in double experiments, see Fig. 14. Note that slightly higher temperatures are recorded when using salt water and X-seed 100 accelerators. A further increase in temperature can be obtained with a cement paste with a low gypsum content. This can be partly used to achieve higher temperatures in the stabilized soil samples but also to start the reactions of binders with a lower degree of reactivity.

5 CONCLUSIONS

By adding accelerators to the binders, we evaluated the shear strength, UCS, and the stiffness of soil using laboratory experiments and statistical analysis. We performed a soil stabilization of soft and expansive fine-grained clays collected in southern Sweden. We evaluated alternative accelerators (X-seed, PCC, LKD and salt) as strength-enhancing admixtures used for stabilization of the soil. Although the major effects came from the binder themselves, a certain contribution to the gain of strength was also noted from the accelerators. Besides, we analysed the effects of varying the curing temperature on the properties of the specimens stabilized. To this end, we evaluated the properties of soil at two temperatures (7°C and 20°C) using a simplified calorimeter and thermos. Moreover, we experimented with fabricating the samples and determined that specimens with an initial height of 100 mm worked well. Our method resulted in a lower standard deviation, compared to the traditional approaches. However, this should be verified by supplementary experiments in future studies. The total time required for the fabrication, trimming, and handling of the specimens was slightly longer compared to the traditional procedures.

Adding accelerators as additional materials along with the use of traditional binders for improving stabilization is worthwhile, even to a minor degree. In addition to the technical benefits, some of the residual products, such as fly ash, have a lower reactivity and are usually less exothermic. The results indicated that the accelerators tested do not work in conjunction with the dry method, which is the most common method of testing soil in Sweden, where the binder is mixed dry. The reason for this is assumed to be due to the lack of free water in the matrix. However, adding PCC with a low gypsum content to the soil mixture worked satisfactorily with regard to the dry method. In this study we evaluated the effects from the accelerators using the wet method, which means that the binder is initially mixed with water and then with soil. Furthermore, this technique has potential in connection with the stabilization of dredged soil to accelerate the curing and to reduce or prevent early leaching. The study included specimens cured under different temperatures and stabilized by different binder mixtures with and without accelerators, which were tested by UCS and measured by the seismic velocities of P-waves. Increasing the curing temperature of the stabilized specimens resulted in a notably faster gain in strength and higher shear strength values, which were detected by P-wave sonic tests and plotted on graphs.

This study evaluated the effects from adding accelerators to other binders, which, to a certain extent, contribute to the gain in strength in soil. In turn, the increased strength of soil stabilized by cement and cementitious materials allows for its higher suitability in such geotechnical engineering works as road or highway construction. Besides, the use of accelerators can lead to a reduced amount of binder used, which reduces negative environmental effects, e.g., from cement, which are caused by the CO_2 emissions associated with cementitious products. The stabilization of soil enhances its performance characteristics, improves its bearing capacity and durability, and ensures safe and stable constructions in geotechnical works. Finally, other advantages of using accelerators consist in their economic effects (reduced costs of the soil stabilization process). These results can be considered when selecting soil stabilization methods in the construction industry.

Acknowledgements

The authors gratefully acknowledge the technical contributions of Martin Holmén and Fredrik Burman, staff personnel from the Swedish Geotechnical Institute (SGI).

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sciendo

Slovak Journal
of Civil Engineering

Vol. 31, 2023, No. 1, 22 – 33
DOI: 10.2478/sjce-2023-0003

DAM INCIDENTS AND FAILURES – CASES IN THE CZECH REPUBLIC

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Abstract

Dam incidents and failures mainly occur during extreme floods. In the Czech Republic (CR), large-scale regional floods were recorded in different regions in 1985, 1987, 1997, 2002, 2006, 2010, and 2013, while local floods especially occurred in 1991, 1996, 1997, 1998, 2002, 2004, 2005, 2009, and 2010. During these events, numerous incidents and total breaches of small dams were recorded, and a few large dams were also critically endangered, although they were not completely breached. This paper presents a comprehensive summary of incidents and failures affecting small dams in the CR since 1985. The most significant incidents concerning large dams are listed as well. The statistics show that 62 small dams were completely breached and that 350 were seriously damaged over 35 years in the period 1985–2020. The annual frequency amounts to 1.85 collapsed and 10 small damaged dams per year. The most common causes of the complete breaching of dams were overtopping (85 %) and internal erosion (15 %).

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Key words

- *Dam,*
- *Inciden*
- *Breach,*
- *Historical cases,*
- *Floods.*

1 INTRODUCTION

Although dams bring many benefits to society, these structures also pose a potential risk if breached. Dam failure incidents, sometimes resulting in total collapse, occur primarily during extreme floods and are usually associated with inadequate spillway capacity, spillway blockage, improper gate operations, or blockages combined with dam crest subsidence. Internal erosion is one of the factors frequently contributing to defects in dams. In the Czech Republic (CR), dams are classified into 4 categories according to the consequences in the case of their total collapse. The first category contains the most important and highest dams, while the fourth category mostly features small dams and ponds. In the CR, there are 462 dams in categories I to III (MA a, 2021) and about 20, 000 dams in the fourth category. Of the latter, 937 are of greater importance (MA b, 2021). Some of these dams are historical embankments that served as ponds and were built between the 9th and 12th centuries (David, 2020). These older dams were constructed without sound knowledge of hydrology, soil mechanics, and hydraulics. Experience shows that about 2 to 10 small dams of less than 9 m in height according to (ČSN 75 2410, 2011) collapse due to overtopping during a typical extreme flood event, including both regional and flash floods (Guideline 10/98, 1998; Guideline 1/10, 2010). Various hazardous events have been documented at large dams during extreme floods since 1985, with one masonry dam being overtopped and a few dams nearly overtopped or breached by internal erosion.

The data on historical dam incidents and failures provide important lessons and the awareness that no dam is safe and that the existence and operation of dams involves a certain degree of risk, even if very small, that must be maintained at acceptable levels (Guideline 1/10, 2010). However, there is generally no desire to publish sensitive „live“ data and point a finger at the bodies responsible for dam construction, maintenance, operations, and monitoring. However, historical data can be useful for analysing the causes and locations of breaches and provide a source for statistical analysis, the evaluation of potential risks, and the calibration and verification of mathematical models of dam failure (Wu, 2013; Froehlich, 2016; Rong et al., 2020).

Historical data on dam incidents and failures from cases around the world can be obtained from numerous sources, namely ICOLD publications (ICOLD, 1974; Bulletin 99, 1995; Bulletin 111, 1998) or other technical documents (DSO, 1992; Singh, 1996; Wahl, 1998; Foster et al., 2000; Coleman et al., 2002; Xu, 2010; Zhang et al., 2016). Bernard-Garcia and Mahdi (2020) assembled a database of dam failures, which currently contains more than 3500 dam break cases. Individual case studies are described and discussed in more detail in forensic reports and technical and scientific papers related to specific dam failures, such as Teton (IPRCTDF, 1976), (Quarantelli, 1979), Big Bay (Ferguson et al., 2004), Malpasset (Goodman, 2013), etc. Significant dam failure accident reports and case studies are also available on websites such as (ASDSO, 2021).

In the CR, information on dam incidents and failures, including those affecting small dams, has not yet been systematically summarized, the published data being limited and scattered across individual documents (Poláček, 1997; Šimek, 1997; Říha, 2004; Říha and Švancara, 2006; Říha and Jandora, 2007). Only a small number of breached dams have been studied in detail (Šobr et al., 2008; Jandora and Říha, 2008; Raška and Emera, 2014). Some data on floods and dam incidents can be obtained from Ministry of Environment reports (CHMI, 1991, 1998, 2002, 2006, 2009, 2010, 2013) and technical monitoring protocols (VDTBD, 2021). The results of forensic assessments are rarely published in technical journals (Hodák, 2015). This paper aims to fill this gap and to provide professionals with a summary of dam incidents and breaches in the Czech Republic over recent decades by detailing key cases and lessons learned.

2 SUMMARY OF DAM INCIDENTS AND FAILURES

2.1 Floods in the Czech Republic

Incidents and failures affecting dams occur mostly during flood events. The consequences of floods and related dam incidents and failures practically always involve considerable material losses, as well as the loss of life in many cases.

The following local floods were witnessed and documented (Fig. 1):

1991 – local August flood in the upper part of the Otava river basin and the Malše river basin,
1996 – local May flood in the Krnov region,
1996 – local June flood in the Blanice basin,
1998 – local July flood in the Orlice river basin,
2002 – local July flood in the Blansko region,
2004 – local July flood in the Ledeč nad Sázavou region,
2005 – local March floods in the Odra and upper part of the Morava river basins,
2006 – local August flood in the northeastern part of Bohemia,
2006 – local June flood in the Dyje river basins,
2009 – local July and August floods in the Jičínka and Bečva river basins,
2010 – local August floods in the Lužická Nisa, Smědá, Ploučnice, Kamenice and Mandava river basins.
2018 – local June flood in the Brtnice river basin.

Regional floods on record were as follows (Fig. 2):
1985 – regional flood, which mostly impacted the Morava river basin,
1987 – regional January flood, which impacted all the river basins in the Czech Republic,
1997 – regional July flood, which mostly impacted the Moravian and Silesian regions,
2002 – regional August flood in the Bohemian part of the CR,

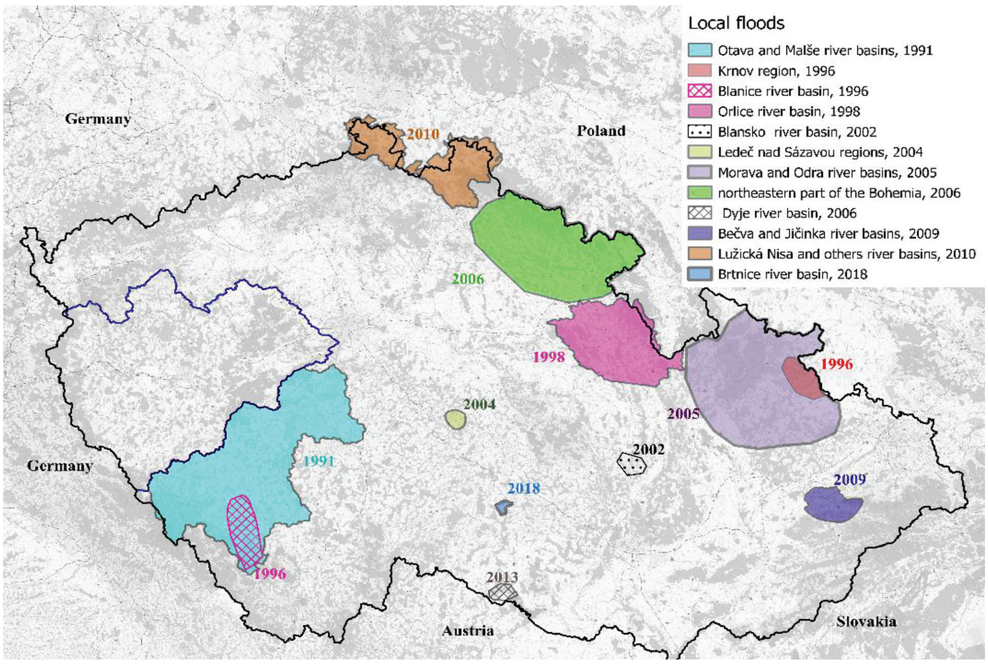

Fig. 1 *The spatial location of local floods in the Czech Republic from 1985 - 2020*

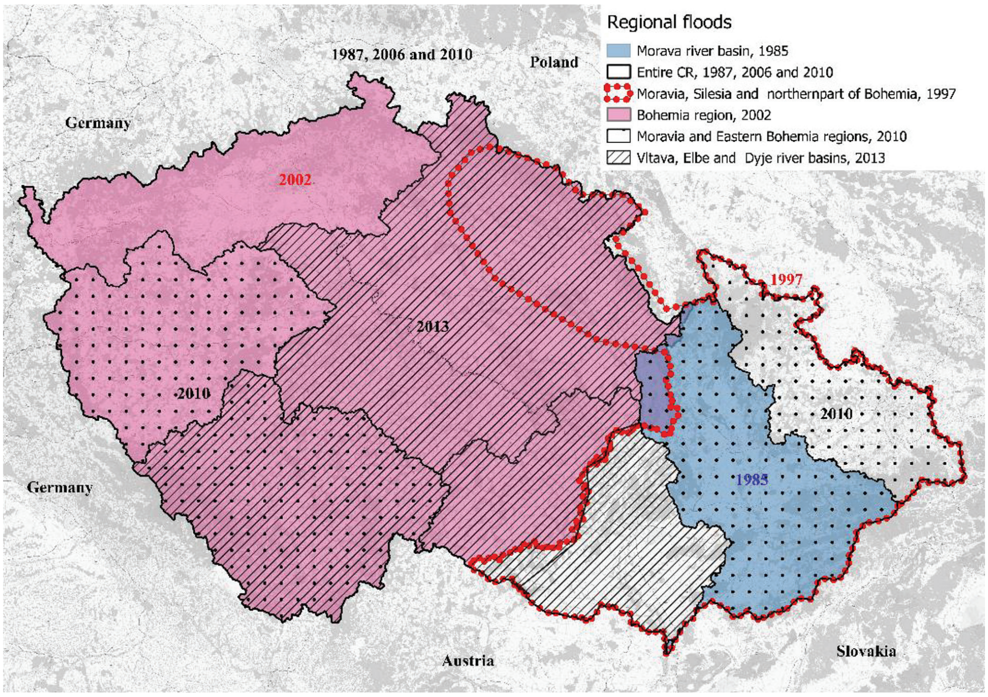

Fig. 2 *The spatial location of regional floods in the Czech Republic from 1985 - 2020*

2006 – regional March flood, which impacted all the river basins in the Czech Republic,
2010 – regional May and early June floods. The first one impacted Moravia, especially the Beskydy mountains and their northern foothills, while the second one impacted southern and eastern Bohemia
2010 – regional August floods, which impacted all the river basins in the Czech Republic,
2013 – regional June floods, which impacted the Vltava river basin, a significant part of the Elbe river basin, and, marginally, the Dyje river basin.

2.2 Small dams

Small dams are defined in the CR as structures with a height of up to 9 m and a total reservoir volume that does not exceed 2 million m^3. The CR has about 20, 000 small dams serving various purposes, mainly fish production and environmental sustainability. Most of them are of relatively low importance and belong to the fourth category of dams (the class of dams with the lowest importance and consequences).

Such small facilities are generally located in the upper portions of river basins and are thus exposed to relatively short storm events with high rainfall intensity. However, many small dams are also exposed to regional floods of long durations associated with high daily totals when the soil surface is fully saturated and induces high surface runoff.

The extensive development of small dams in the CR has its roots in the 12th century. The oldest documented small embankment dam, i.e. Žár, was built in 1221 (David, 2020). In this period, small dams were being built for fish farming, which further developed in the CR at the end of the 15th century and in the first half of the 16th. In the following 3 centuries, there was stagnation in the development of the design and construction of small dams in the CR. The revival of dam construction dates back to the end of the 19th century, when numerous small dams were built or renovated for water supply, recreation, and fish farming. In recent decades, small „dry“ detention reservoirs have been built for flood control.

Because of their age, some small dams suffer from extensive seepage and local landslides. Moreover, the spillway capacity is inadequate at most old facilities. Because of a large number of facilities and the large number of owners, small dams are often poorly maintained, and the necessary reconstruction and rehabilitation works are not performed in time due to a lack of funding. In addition, many owners of small dams are not skilled enough to adequately assess the condition of their facilities and remedy problems.

These circumstances lead to many minor incidents, but can also result in the complete failure of the dam. The latter mainly occur when dams are overloaded, namely, during the extreme flood. For example, during recent severe floods in 2002, 2009, and 2013, dozens of small dams were breached as a result of the crest overtopping or by piping. These were mostly ponds and small water reservoirs situated in the upper parts of basins affected by heavy rainfalls, where peak discharges exceeded a return period of a hundred years, and, in some places, as much as 500 years (CHMI, 1991, 1998, 2002, 2006, 2009, 2010 and 2013; TSR, 2021). An extensive search was conducted on the events impacting small dams since 1985, and the resulting overview in Tab. 1 was compiled based on of the available sources (CHMI, 1991, 1998, 2002, 2006, 2009, 2010, 2013; TSR, 2021; Poláček, 1997; Říha, 2004; Šobr et al., 2008). Failures and incidents that occurred before 1985 have not been systemically observed and registered (Elleder et al., 2016; David, 2020).

The first more reliable records concerning breached fourth category small dams date from the year 1985, when the owners themselves began making a dam breach inventory. However, these records are often incomplete or missing, e.g., the basic parameters of the ponds or the causes of the breaching. In that

Tab. 1 *Summary of breached and significantly damaged small dams during floods in the Czech Republic from 1985-2020*

Year	Number of breached small dams	Number of damaged small dams	Comment
1985	5	41	100 % overtopping
1986	1	0	100 % internal erosion
1987	2	4	100 % overtopping
1991	1	0	100 % overtopping
1997	1	1	100 % overtopping
2002	23	93	100 % overtopping
2004	0	1	100 % overtopping
2005	0	3	33 % overtopping and 66 % internal erosion
2006	5	15	50 % overtopping and 50 % internal erosion
2007	0	3	100 % internal erosion
2008	0	2	100 % internal erosion
2009	6	54	92 % overtopping and 8 % internal erosion
2010	8	13	77 % overtopping and 23 % internal erosion
2011	0	3	66 % overtopping and 33 % internal erosion
2012	1	2	33 % overtopping and 66 % internal erosion
2013	7	23	93 % overtopping and 7 % internal erosion
2014	1	13	29 % overtopping and 71 % internal erosion
2015	3	0	100 % internal erosion
2016	1	1	50 % overtopping and 50 % internal erosion
2017	0	0	100 % internal erosion
2019	0	7	100 % internal erosion
2020	1	5	33 % overtopping and 66 % internal erosion

year, 41 small dams were damaged, and 5 were breached according to the records. The most severe event on record was a regional flood in 2002, when 23 small dams completely failed, 9 of them in a system of two parallel dam cascades (see Section 3.1). During a local flood in 2009, only 3 dams were breached, but more than 30 were damaged by overtopping, very often at a location where the crest had a decreased height. Finally, in the 2013 regional flood, 5 small dams were breached, and 7 were significantly damaged.

From the lists in Tab. 1, it can be seen that the majority of small dams collapsed during the regional flood in 2002 and that extensive damage also occurred during the local „flash“ flood in 2009, when not so many total failures occurred due to the relatively short duration of the flood. The most important cases of small dam failures are described in Section 3.

The floods that most impacted dams occurred in 1985, 1997, 2002, and 2009. In 1997 when the regional July flood occurred mostly in the Moravian and Silesian regions, only one dam was damaged. When a regional August flood occurred in the Bohemian part of the CR in 2002, it damaged 93 dams and breached 23. In 2009, when local floods occurred in July and August in the Jičínka and Bečva river basins, up to 120 small dams were damaged and 6 breached.

According to the list of collapsed and severely damaged small dams, 62 of them have been fully breached, and 350 were severely damaged between 1985 and 2020 (Tab. 1). On average, there are 1.85 breached and 10 damaged small dams per year. The most common causes of the complete breach of dams were overtopping (85 %) and internal erosion (15 %), while in 5 cases, internal erosion was combined with overtopping. At small dams incidents during regular normal no-flood operations are related to internal erosion along the bottom outlet (60 %), gate or valve failure (35 %), and rodents (5 %). Slope instability has been unusual as a causal factor.

2.3 Large dams

Generally, large dams are more carefully and professionally designed and maintained by skilled staff. The only large dam that has been completely breached in the CR was the Bílá Desná Dam, which failed in 1916 due to its piping. This was the worst dam disaster in the Czech history and has been described in numerous publications (Šimek, 1997; Saxena and Sarma, 2004; Raška and Emmer, 2014). Therefore, this study does not deal with this event, which is more than 100 years old. Nevertheless, there have been numerous major dam incidents and emergencies in recent years, most of which were

Tab. 2 *List of large dams endangered/damaged during floods in the Czech Republic from 1985*

Year	Name / Type / Category	Water Course/ Stream	Dam Height	Volume [ths. m^3]	Comment
1996	the Morávka Dam/ E / II	Morávka	39	12,100	collapse of upstream asphaltic lining due to internal erosion
	the Pocheň Dam / E / III	Čižina	9.5	817	overtopping, emergency opening
1997	the Šance Dam / R / I	Ostravice	65	61,800	insufficient spillway capacity, slide of the bank initiated
	the Pocheň Dam / E / III	Čižina	9.5	817	overtopping, emergency channel
2002	the Orlík Dam / G / I	Vltava	91	720,000	water entered the dam body
	the Znojmo Dam / C / I	Dyje	17	4,290	spillway clogged by floating debris
2004	the Mostiště Dam / R / I	Oslava	28.7	11,937	clayey core collapsed due to piping
2010	the Mlýnice Dam / M / III	Albrechtický	22	271	overtopped, foundation scour

Dam type: C – combined, E – embankment, G – concrete gravity, M – masonry, R – rockfill

associated with both flood situations and internal erosion. A summary of the most significant events can be found in Tab. 2.

However, no large dam has completely collapsed since the Bílá Desná Dam disaster in 1916, and all hazardous situations have been successfully managed. As a rule, remedial measures have always been prepared and adopted a few years after the incident. In some cases, provisional remedial measures had to be carried out before final repairs were initiated in order to prevent the proximate damage from further developing the defect, see Section 4.

3 MAJOR FAILURES AND INCIDENTS AT SMALL DAMS

The following text describes and discusses the most important and best-documented small dam failure events. The most extensive set of breaches of small dams in the Lomnice river basin in the Blatná region in 2002 was selected for a detailed analysis, together with a description of the well-documented failure of the small Mlékovice Dam during the 2013 flood. These were some of the most dangerous dam breaches of recent decades in the Czech Republic.

3.1 The domino effect in the Blatná region

Historically, floods in the Lomnice river basin have always been extensive. The oldest report of flooding dates back to 1586, when the spring snowmelt destroyed 18 ponds in the region. During the catastrophic spring flood in 1895 all the ponds were breached. In 1987, the Lomnice basin was affected by a summer flood, but only two dams (the Veský and Podhájský) were breached and one pond was damaged. The main reason for the failures was insufficient spillway capacity. The most dangerous situation in recent years occurred in the Lomnice river basin in August 2002, when floods occurred after two waves of heavy rainfall. The total daily precipitation was between 200 and 350 mm, depending on the locality. Within the basin area of the Lomnice River and Závišínský Stream, nine small dams collapsed in two parallel cascades as a result of the breaching of two small dams in the upper part of the cascades. Two other small dams were severely damaged but not completely breached. Several villages were completely flooded. Fortunately, due to the successful evacuation of the inhabitants, only one person died due to drowning.

This critical situation started on 13 August 2002, at the western cascade where the uppermost small dam called Melín was breached due to overtopping. In a few minutes, the dam´s break wave approached the lower lying reservoir Metelský, which was rapidly impounded resulting in the dam breach in two places (Fig. 3). In the case of the Metelský Dam, an old part of the cracked wooden outlet was found a few hundred meters downstream of the dam. The subsidence of the dam crest at the site of the wooden bottom outlet indicates internal erosion of the soil down close to the cracked pipe. The villages of Metly and Předmíř were completely inundated. The next dam in the cascade, the Veský Dam, was eroded on its downstream slope due to overtopping, but it was not breached as the crest was protected by an asphalt road. A similar situation was observed at the Zámecký Pond. The lower-lying village of Lnáře was seriously damaged. The progression of internal erosion was observed at the Podhájský Dam. The reconstruction of the dam had been completed 13 years before the event. The reconstruction consisted in the installation of a central slurry wall built using jet grouting technology. During the overtopping, the downstream shoulder was eroded, and the slurry collapsed. Other dams downstream (the Hořejší and Dolejší) downstream failed due to overtopping as the capacity of the spillways was not enough to manage the flood coming from the upper ponds. Here, surface erosion played the most important role. The village of Tchořovice was completely inundated, and many houses, local roads, and railway were destroyed too.

At the same time, three dams failed in the parallel cascade on Závišinský Stream. First, the dam of Luh Dam was breached due to a long period of overtopping over a length of about 120 m with a nappe height of about 20 cm, which initiated local landslides of the downstream slope. The subsequent breach of the Velký Bělčický Dam was due to the increased inflow from the Luh pond and the extreme hydrological situation at the intermediate catchment. At this pond appurtenant works (the outlets, spillway, etc.) were clogged and not in operation due to poor maintenance. The dam crest was overtopped and the dam of Velký Bělčický Pond breached in a relatively short time. The village of Bezdědovice was completely inundated. As the pond served as the local water supply, the surrounding villages lost their water source. Another pond called the Pustý lying downstream was rapidly breached due to overtopping as the incoming dam break flood significantly exceeded the capacity of the spillways. Another single pond, the Buzický, was breached as a result of the extreme hydrological situation when the screens at the appurtenant works became clogged and the regulation mechanism was not operating due to unsatisfactory technical conditions.

Five years after the event, the Czech Hydrometeorological Institute recalculated the design flood discharges for the affected dams, increasing them almost two times. Appurtenant works for all the ponds in the basin were adapted to the new parameters. The use of fixed rather than gated spillways became a priority, as there was no need to manipulate them during a flood (the Pustý, Velký Bělčický, Luh, etc.).

Fig. 3 *The breached Metelský Dam (photo by authors)*

3.2 Mlékovický Pond

Mlékovický Pond is fed by Miletínský Stream with the basin area counting over 40 km^2. The dam was of a homogenous embankment. The upstream slope was lined by a stone revetment, while the downstream slope was grassed. The maximum dam height was 6 m with a crest length of 160 m. The first record of the Mlékovice Pond fourth category dam can be found in the Ist (Josephian) military maps, dating from 1764 - 1768 (David, 2020). The pond had two spillways, one at the left

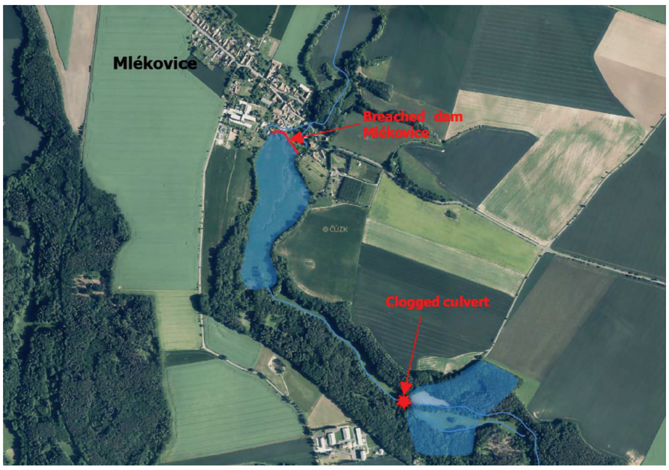

Fig. 4 *The location of Mlékovice Pond*

abutment with a capacity 16 m^3/s, and the second one at the right abutment with a capacity of approximately 8 m^3/s. The main purpose of the Mlékovice Pond was the protection of the village below the dam against flash floods.

During the flash flood in June 2013, the peak inflow to the Mlékovice Pond was recorded on 2 June 2013 in the morning. The hydrological flood wave in the basin was increased by clogging and the rupture of the culvert at the road crossing Miletínský Stream upstream of the dam (Fig. 4). The resultant flood wave with an estimated peak discharge of 50 m^3/s significantly exceeded the capacity of the spillways, which caused overtopping of the dam crest. In a short time, erosion initiated the breach (Fig. 5).

Fig. 5 *The breach in the Mlékovice Dam during the 2013 flood (Švarc, 2014)*

Just after the flood, extensive remediation works were carried out at the dam site to ensure the safety of the settlements below the dam. A provisional flood levee was constructed for the water transfer. This was followed by remediation of the scour downstream of the breach. The transfer of water across the dam was checked shortly after the event on 25 and 26 June, when Miletínský Stream experienced a flood with a return period of about 5 to 10 years. The pond has been repaired, but it has never been completely filled up with water again and is currently out of operation.

4 FAILURES AND INCIDENTS AT LARGE DAMS

In this section, selected incidents are described in which an emergency state was declared at the dam in question, and corrective actions were implemented to ensure dam safety. The Pocheň Dam and Mlýnice Dam were the large dams most affected by overtopping. In the case of the Znojmo Dam, a risk of overtopping arose due to the blocking of spillways by floating debris. The Morávka Dam and Mostiště Dam were significantly affected by internal erosion.

4.1 The Pocheň dam

The Pocheň Dam (third category) is located on the Čižina River close to the municipality of Krnov. It is a zonal, nonhomogeneous embankment dam with a core made of cohesive, relatively impermeable, clayey soil and with shoulders made of less cohesive gravel soil. The construction of the Pocheň Dam was completed in 1975. The maximum dam height is 9.5 m, with a crest length of 175 m. The lateral spillway is located at the left abutment. The main purpose of the dam is flood protection and recreation.

The first overtopping of the Pocheň Dam occurred in 1977, two years after its completion. The dam was overtopped along its entire length, and the downstream slope was significantly eroded. The second overtopping was in 1996, when heavy rainfall occurred in the Čižina river basin. The culmination of the flash flood occurred during the night of 13 to 14 May. The reservoir's maximum water level was reached quickly, and the dam started to be overtopped with a 0.3 to 0.4 m high nappe (Fig. 6), which eroded a 1 m deep layer at the downstream slope. The soil volume washed away was around 3, 000 m^3. A slope of 1:1 to 1:1.3 was formed along the downstream side. The spillway was damaged during the flood, which undermined the prefabricated bottom of the spillway chute.

In the spring of 1997, a regional flood occurred in the Moravian region, and the Pocheň Dam was overtopped again. A temporary channel excavated at the left abutment helped the flood to pass through the dam profile, though serious damage was done to the dam body.

The main cause of the overtopping and damage to the Pocheň Dam was the extreme flood situation, which occurred relative to the extraordinary rainfall with a return period of higher than 100 years. A retrospective analysis of the spillway hydraulics confirmed that the spillway had insufficient capacity to transfer a flood with the newly declared return period of 20 years. Another problem was the insufficient freeboard combined with local subsidence of the dam crest (VD-TBD, 2021).

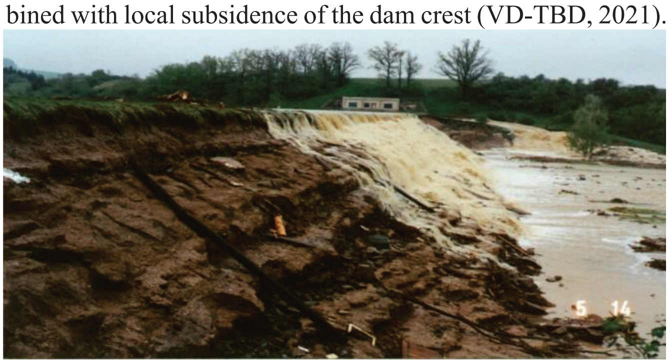

Fig. 6 *Overtopping of the Pocheň Dam during the flood in 1996 (VD-TBD, 2021)*

In order to bring the damaged dam into a sustainable and safe condition, the repair of the dam body, the redesign of the spillway, a new fish pass, and technical measures for completely ensuring the reliable operation of the bottom outlet during operations was implemented. The reconstruction of the dam was completed in 1998.

4.2 The Morávka Dam

The Morávka Dam (second category) is located on the Morávka River close to the municipality of Frýdek Místek. It is an embankment dam originally provided with an asphaltic concrete lining connected to a grouting gallery (Fig. 7). The construction of the Morávka Dam was completed in 1967; it was the first earthfill dam with a bituminous lining in the Czech Republic. The dam height is 39 m, with a crest length of 396 m. The main purpose of the dam is water supply to the population, flood protection, and hydropower generation.

During the decades the asphalt face degraded, namely, due to the seepage instability of the fill material below the lining. The surface of the slope became uneven with numerous depressions indicating missing material and the development of local caverns below the face. The internal process was accelerated by the seepage coming from the left abutment combined with local leaks through the sealing. The asphaltic lining below the permanent storage level experienced serious damage after a flood in 1996 when the sealing cracked counting the area approximately 10 m^2 (Figs. 7, 8). The material of the dam body under the sealing was being transferred to the foundation due to leaks in the sealing (Březina et al., 1998; Kratochvíl and Glac, 2006). The dam was completely reconstructed in the years 1997 – 2000, including an upgrade of the existing bottom outlets, the installation of a new bypass tunnel with additional bottom outlets, the reconstruction of the sealing by milling the upper layers and replacing them with a Sibelon PVC geomembrane, and the drilling of a drainage tunnel at the left abutment.

Fig. 8 *Failure of the bituminous concrete facing of the Morávka Dam in 1996 (VD-TBD, 2021)*

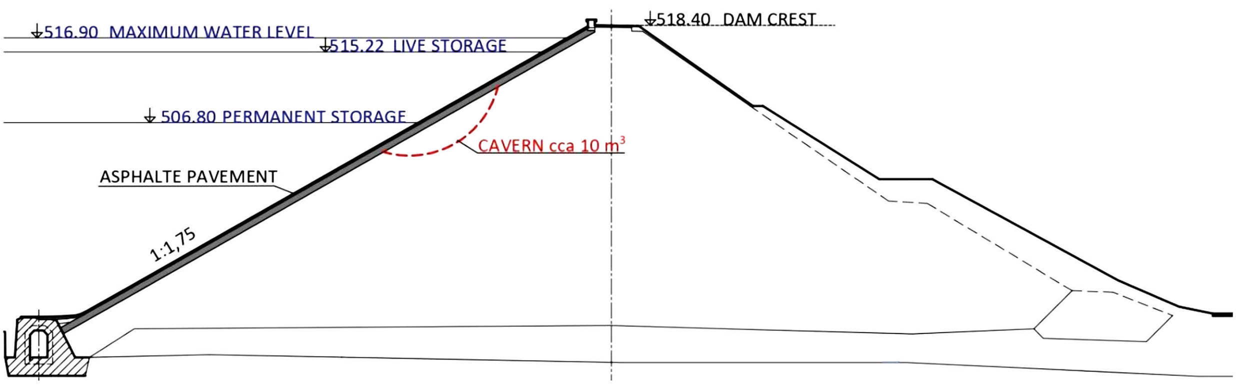

Fig. 7 *Typical cross-section of the Morávka Dam*

Fig. 9 *The original spillway almost choked up during the flood in 2002 (VD-TBD, 2021)*

Fig. 10 *Reconstructed spillway with steel traps during the flood in 2006 (VD-TBD, 2021)*

4.3 The Znojmo Dam

The Znojmo Dam (first category) is located on the Dyje River, which is close to the Austrian border. The 20 m high dam is zonal with a central loess core. The dam is equipped with a functional concrete block with bottom outlets, a hydropower plant, and a spillway (Fig 9). The construction of the dam was completed in 1966. The main purpose of the dam is to stabilize the peak flow rates coming from the higher-lying Vranov hydropower plant. The original spillway consisted of two spans gated with flaps. The spillway capacity was 413 m³/s.

A flood wave with a peak discharge of 380 m³/s arrived at the Znojmo reservoir in August 2002. During the flood, the spillway was obstructed by floating debris coming from the natural park upstream of the dam, where no timber management is permitted. Due to the decreased spillway capacity (Fig. 9), the dam was endangered by potential overtopping; sandbags were installed along the dam crest; and floating debris from the spillway was removed by a heavy crane installed on the dam crest. After the performance of comprehensive studies, including hydraulic research (Stara et al., 2006), the spillway was completely reconstructed in 2005. The level of the fixed spillway crest was reduced, new sector gates were installed; the spillway forebay was equipped with steel racks; and the stilling basin was extended and equipped with baffles. The efficiency of the improvements was checked during a flood in 2006 (Fig. 10).

4.4 The Mostiště Dam

The Mostiště Dam (first category) is located on the Oslava River upstream of the town of Velké Meziříčí. The dam height is 29 m, and the crest length is 292 m. The dam is made of quarry rock with an inclined clayey core (Fig. 11). The foundation rock is sealed by a single-row grout curtain. The Mostiště Dam was completed in 1960, when it was the first rockfill dam in the CR. The main purpose of the dam is to supply drinking water. The flood protection effect of the dam is relatively small.

Technical dam safety inspections and surveillance have indicated increased seepage through the dam body since 1996, namely during floods when the water level exceeded 476.10 m above SWL. The leakage could not be localized due to the absence of a toe drain. The dam behavior called for additional surveys focused on the possible locations of potential defects. Monitoring indicated unusual subsidence of the dam crest at the right abutment. After dismantling the crest in 2004, a cavern was discovered in the core covering an area of several square meters. The defect was assessed as the hydraulic fracturing of the impervious core in at least two places close to a water level of 476.10 m above SWL. The geological survey indicated the potential damage in a thin horizontal layer in the core, where the sandy loess was not meeting self-filtration criteria. Careful investigation of old records from the dam construction indicated heterogeneous core material at some locations containing sandy lenses. Moreover, the upper, thinner part of the core was poorly compacted due to the use of inadequate compacting equipment. Even transition zones (filters) were missing at some places and locally failed to meet non-suffosion criteria.

In 2005, repairs were carried out consisting in the creation of a continuous inclined sealing barrier via directed jet grouting technology to a depth of 7 m along the entire length of the dam (Říha and Švancara, 2006; Švancara and Krejčí, 2009). The filters were improved by “flushing in” additional sandy material, and the drainage system was improved by the addi-

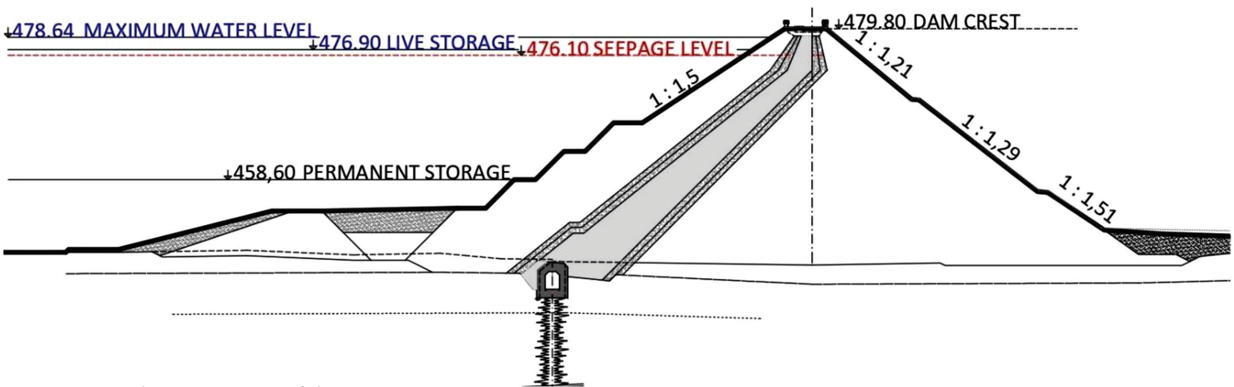

Fig. 11 *Typical cross-section of the Mostiště Dam*

tion of horizontal drains and pore pressure measurements in the walls of the grouting gallery.

4.5 The Mlýnice Dam

The masonry Mlýnice Dam (third category) is located on Albrechtický Stream southeast of the village of Albrechtice. The dam is 14.5 m high, masonry, with a 159 m long crest. The Mlýnice Dam was completed in 1906. Its main purpose is flood attenuation along the River Lužická Nisa.

After heavy rain on 6 August 2010, the water level in the reservoir reached the spillway crest. The spillway capacity was partially reduced by floating debris. The bottom outlets were immediately employed, but the water level in the reservoir rapidly rose by 1.5 m in 30 minutes. At that time the water level reached the dam crest, which was overtopped along its entire length (Fig. 12). Moreover, a blackout occurred at the locality, which caused the bottom outlets to remain only partially opened. Manual operation of the gates was not possible due to the overtopping of the crest. The crest was overtopped for about 40 minutes. The water level in the reservoir culminated at approximately 16 cm above the dam crest with an estimated peak flow rate 65 m^3/s, which is more than 3.6 times exceeding discharge with a 100-year return period and more than 1.5 times the peak discharge of a controlled flood. The overtopped water eroded deep scours along the entire abutments downstream of the dam (Fig. 12). However, the dam's stability was not harmed due to the relatively short overtopping time.

Fig. 12 *Overtopping of the Mlýnice Dam during the flood in 2010 (VD-TBD, 2021)*

To ensure the dam´s stability the erosion holes were cleaned and filled with plain concrete. Stepped slabs were installed to stabilize the exposed toe of the dam at the abutments, and the scoured slopes were sprayed with concrete. Finally, the abutments were weighed with heavy stones with a weight of about 1t per piece. At present, the overtopped crest is considered to be an “emergency spillway”.

5 CONCLUSIONS

In the paper a summary of defects and failures affecting small dams and serious incidents at large dams in the Czech Republic since the year 1985 is presented.

Historical records show that during the period of 1985 – 2020, about 62 small dams were completely breached and 350 were seriously damaged. This is an annual frequency of 1.85 collapsed and 10 damaged small dams. About 85 % of the small dams failed due to overtopping, while about 15 % of the failures were due to internal erosion. Other reasons are quite rare. The records and assessments of the incidents and failures affecting small dams show that the following factors influence the related risks:

- Due to the great number of small dams (about 20, 000 in the CR) and the variety of mostly private, owners, the necessary maintenance, reconstruction, and rehabilitation works are not always carried out. In some cases, the appurtenant works are in poor condition. The reasons for this include a lack of skill and funding. An inventory of the main defects found at small dams (Říha, 2013) includes the poor condition of the bottom outlets (40 %), unmaintained vegetation on the dam body (35 %), seepage problems (40 %), depressions in the dam crest and slopes (30 %), the poor technical condition of the spillway (26 %), and insufficient spillway capacity (45 %).
- Due to their lesser importance, the design of small dams and their construction and technical monitoring are often insufficient. The required activities are performed by less skilled and inexperienced parties, who win tenders by offering the lowest bid.
- As most small dams belong to the fourth category, technical surveillance is restricted to visual inspections in standard cases, with reporting required once every 10 years. Basic technical documentation is often missing, namely, in the case of historical ponds.
- During a flood, the crucial issue is spillway capacity. This is often insufficient due to poor knowledge of the hydrological data (at historical ponds) and inadequate hydraulic design and maintenance (trees in the chute profile, etc.). Another reason is that for most fourth category dams, the required design and check floods correspond to a return period of 100 years. In many cases, the dams experience more severe floods with a return period exceeding 500 years. A recent recommendation is to design spillways for the maximum probable flood or at least to provide the scheme with an emergency spillway.
- A cascade may contain numerous ponds (section 3.1) with many different private owners. Usually, these small reservoirs or ponds do not have consistent design characteristics and are maintained and monitored in different ways. If an upper one fails, the dam break flood progression downstream causing the breaching of lower lying small dams.
- The breaching of a dam body or the development of seepage has mostly occurred at locations where unprofessional modifications had been made. These can include heavy traffic on the dam crest, the excavation of soil material on the downstream slope, the planting of trees on the dam, etc.
- After a given incident, remedial measures are often adopted late at most dams listed in the fourth category, inadequately or even not at all.

In the case of large dams, more careful design, construction, and technical surveillance are the rule. Therefore, no large dams have failed in the CR since 1916, when the Bílá Desná Dam collapsed. It can be stated that all hazardous situations with large dams have been successfully managed and that remedial measures have been adopted as soon as possible after the incident. In case of an immediate hazard, provisional arrangements have been adopted before the beginning of final repairs. In many cases, conceptual studies were performed as a basis for the total reconstruction of the scheme. The following may be stated:

- Large dams are managed by professional bodies such as river boards or hydropower companies.
- Regular dam surveillance and monitoring are performed by professionals appointed by the Ministry of Agriculture.
- The design parameters are periodically verified based on actual hydrological data.
- After incidents, costly remedial measures usually amounting to several million Euros have been adopted based on comprehensive feasibility studies, including cost-benefit and risk analyses.

Even if statistical data about dam failures and incidents may be a valuable source of general information about the frequency of such cases, each dam is a unique structure, and it is necessary to perform a safety assessment, design, construction, and surveillance on an individual basis according to local conditions and the type of installation.

Acknowledgment

The paper is a part of Project No. FAST-J-21-7486 of the Brno University of Technology, Faculty of Civil Engineering. Many thanks to the Technical Surveillance of Vodní díla -TBD for providing the Technical Surveillance Records of Dams.

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sciendo Slovak Journal of Civil Engineering
Vol. 31, 2023, No. 1, 34 – 44
DOI: 10.2478/sjce-2023-0004

INVESTIGATION OF THE EFFECTS OF ADDITIVES USED IN REDUCING ASPHALT PRODUCTION TEMPERATURES

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Abstract

This study is related to evaluations of the performance and usability evaluations of existing and also newly produced Warm Mixed Asphalt (WMA) additives. Viscosity, softening point, and penetration tests were performed on bitumen with additives without changing the bitumen rate for the additives. For the asphalt concrete, Marshall Stability tests were performed. WMA additives are used to reduce asphalt production temperatures and, consequently, the temperature of the mixture significantly. According to the Marshall Stability test, it was determined that the WMA samples fulfilled values within the local standards. The Hot Mixed Asphalt (HMA) and Warm Mixed Asphalt (WMA) additives were compared as to additive costs and energy savings considering the reduced production temperatures. Additives have great potential to be used in adverse weather conditions and in many countries.

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Key words

- Warm Mix Asphalt (WMA),
- Hot Mix Asphalt (HMA),
- Modified Bitumen,
- Viscosity,
- Additive,
- Energy Saving.

1 INTRODUCTION

Asphalt surface courses have thicknesses ranging from 20 to 30 mm, depending on various factors such as their design, construction, and maintenance (Morova et al., 2011). Local environmental conditions, the interaction of the materials in a pavement's composition, and the traffic load on the asphalt pavement should be known, as they play a very effective role in the future performance of asphalt concrete (Tosun, 2011). Hot Mix Asphalt (HMA) is made of aggregate that is dried at 145-160ºC and heated to approximately the same temperature, and the bitumen is turned into a viscous liquid. Approximately 95% of the mixture consists of aggregate and 5% bitumen. Owing to the additives used in Warm Mix Asphalt (WMA), the high temperatures in the production of traditional methods could be reduced. In this way, the applicability, workability, and paving of asphalt are easier and provide great advantages (Rahman et al., 2020).

Warm Mix Asphalt was first tested and performed in Europe in Germany and Norway from 1995 to 1999 (Ranken et al., 2019; Cheraghian et al., 2020). In 1996, scientists in Norway performed the first experiments using their new type of asphalt mix called Warm Asphalt Mix (WAM). As a result, they developed WAM Foam, one of the earliest examples of foam technology. In 1997, Hamburg became the first city to use a warm mix asphalt with a wax additive i.e., Sasobit, while an aliphatic hydrocarbon produced by Sasol Wax (Germany) by the Fischer-Tropsch method. The aliphatic hydrocarbon obtained by the Fischer-Tropsch method is defined as a long-chain aliphatic hydrocarbon because it contains more than 40 to 115 carbon atoms. In 1999, the first trials of WMA with foam asphalt and Aspha-min zeolite were conducted in Norway and Germany, respectively. A study conducted by the National Asphalt Pavement Association (NAPA) in 2002 introduced WMA technology to the USA (Cheraghian et al., 2020). Later, synthetic zeolite additive started to be used in WMA technology; the zeolite formation helped the foam to provide ease of movement and workability in the bitumen (Barthel et al., 2005). Many additives and forms have been produced or designed using this technique. WMA has been accepted in 45 countries in America and Europe. It is currently gaining more interest as a new technology but is still trying to be actively implemented in many countries in recent years. It is estimated that most of the asphalt production facilities will be established for WMA in the future by large industrial enterprises (Kim et al., 2012).

The additives are of three types: organic, foam, and chemical additives, respectively (Seth, 2010). Additives that reduce the viscosity of the binder are used to ensure that the aggregate is completely covered and that the compactability of the mixture is at a low temperature. An average 20-40°C reduction in the mixing temperature can be achieved with organic additives. Besides, these additives modify the asphalt to increase its resistance to deformation (EAPA, 2016). These additives act as surfactants at the interface between the aggregates and bitumen. Typically, they regulate and reduce the frictional forces at the interfaces in a range of 85°C to 140°C. Thus, it is possible to mix the bitumen and aggregates at lower temperatures and to compact the prepared mixture. The chemical additives can reduce the mixing and compaction temperature by approximately 20°C (EAPA, 2016).

With the low mixing and compacting temperature achieved by using warm mix asphalt, smoke and odor emissions are reduced to their lowest levels, and a better working environment is provided for asphalt workers. In practice, there is a 50% reduction in the emission of fumes released with every 12°C decrease in temperature (Brandt and Groot, 1999). It is also known that energy consumption decreases by a maximum of 40%, which reduces the production temperature, and this reduction benefits the asphalt production as well as the WMA process (Ruhl and Lindemier, 2006). Although the WMA application seems to have an economic advantage in terms of fuel savings as it provides for pavement production at a lower energy cost, both the facility installation and the cost of the additives almost eliminate this advantage. However, considering its positive effects on the environment, it can be seen that it has more economic benefits over the long term. In countries where fuel is more expensive, WMA can be very economical (Aytekin, 2018). According to the data obtained by some researchers, the greenhouse gas emissions such as CO2, NO2, and SO2 are decreasing at the rate of energy savings achieved; this rate varies between 25% and 50%, depending on the process used. Besides, it was determined by experiments that there is a significant reduction of 30-50% in the output of multi-ring aromatic hydrocarbons (PAHs) with asphalt odor and fumes compared to the hot mix asphalt (FHWAPL, 2008). In a study conducted in Norway in 2011 to compare the applications of warm mix asphalt with hot mix asphalt, it was found that the exposure to bitumen fumes and vapor in warm mix asphalt was significantly lower. In this study in Norway, the working environment of 11 warm mix asphalt and hot mix asphalt trial sections the same day was evaluated. According to the results, with an average decrease of 29°C in the asphalt's temperature, there was a very significant decrease in asphalt fumes, ranging from 58-67% (Norwegian WMA project, 2012).

Issues involving foaming have been investigated in detail, and it has been found that it is beneficial to heat the aggregate for the foaming of the bitumen below 100°C (Kristjánsdóttir, 2007). Larsen et al. worked on WMA production to produce asphalt at temperatures lower than HMA to reduce the energy consumption, bad odors, and smoke emissions. The work specifically focused on foaming WMA (Larsen et al., 2004). Hurley and Prowel (2005) investigated the process of adding Sasobit wax to the mixture by a melting method in their study and reported that the air void contents were less than in other additives. They also examined the interaction with filler and other materials and stated that WMA was better than the traditional method. Johannesson et al. (2005) examined the differences between warm and hot mix applications in Iceland. The report includes some information about and comparisons of different types of pavements used in the country, according to the life cycle costs. In the feasibility study results, it was seen that warm mix asphalt is a less costly option than hot mix asphalt over the long term. Jamshidi et al. (2012), investigated the behaviour of WMA technologies containing Sasobit under load strain, and time factors. The findings obtained in the laboratory and field trials were evaluated. At the same time, the life cycle assessment, the energy-saving potential of the Sasobit mixture, and the potential for a reduction in greenhouse gas emissions were examined, and they achieved positive results. Zhao and Guo (2012), used a test tool to evaluate the workability of WMA with Sasobit. First, a feasibility study was performed with asphalt mortar; then the workability of the WMA was determined at different temperatures and frequencies and compared with the HMA. As a result, it was concluded that WMA with Sasobit reduces the mixture's temperature to close to 30°C and has better workability than HMA and a very similar performance to HMA. The study found that by subjecting the Evothem J1 additive to a Marshall stability test, the temperature of the additive used can reduce the mixture's temperature to 120°C. At the same time, when examining its effect on the humidity, it provides a decrease compared to HMA; its performance does not change or even increase (Mahida et al., 2015). In studies on MCM-41, which is a mesophore (small pore) silica material, Woszuk et al. (2018) revealed that it can be used as a WMA additive in terms of both environmental and economic benefits. At the same time, they showed that this additive, which reduces viscosity at low temperatures, is convenient in terms of its workability. Aktaş et al. (2018) applied viscosity tests to bitumen modified with Evothem M1 and Viatop plus C25 additives at different temperatures; they observed that these additives significantly lower the viscosity at low temperatures and demonstrated the differences in terms of their applicability and workability.

In Denmark, the National Competence Centre (NCC) produces warm mix asphalt with a foam bitumen technique using a patented foaming generator. They carried out a WMA application study on a highway under classic asphalt production conditions. Polymer-modified bituminous stone mastic asphalt was produced, and the production temperature was reduced by approximately 20°C with this technique (EAPA, 2016). The Asphalt Manufacturers Association in Norway started a new project in 2010 on low-temperature asphalt, i.e., "LTA-2011". Within the scope of this project, 11 trial sections were constructed with 6 different techniques; issues in terms of the asphalt workers' health and the quality of the asphalt were investigated, and the production temperature was reduced by approximately 30°C. A trial section was made using zeolite on an urban road section in Istanbul in 2012, and its performance was found to be equivalent to traditional asphalt (EAPA, 2016).

Belc et al. (202)1 investigated WMA additives such as chemical, synthetic zeolite, and organic additives at different mixing temperatures and determined that there was no difference between HMA and WMA characteristics. However, organic additives significantly reduce the mixing temperature by almost 40°C. Ferotti et al. (2017) declared that the effect of chemical additives on bitumen is not significant but that modified bitumen could decrease the viscosity temperature, while increasing the rutting resistance and the elastic responses. A study that dealt with a laboratory investigation of the properties of WMA binders containing polyphosphoric acid showed that the additive increased viscosity (Liu et al., 2018). It was not discussed whether the additive used was organic or chemical. Jattak et al. (2021) used bottom ash to examine the performance of WMA and declared that using bottom ash with Evotherm 3G improved the indirect tensile strength of WMA.

Zhang et al. (2020), examined the water stability performance of WMA with a ZYF-1 additive at a low temperature and recommended a 4% dose. ZYF-1 also reduced the construction temperature of the asphalt mixture. Zhang et al. (2021) evaluated a surfactant additive foamed for modified asphalt and declared that it showed better workability and had a good low-temperature performance. It can be said that most of the studies regarding WMA and its performance show significant developments in terms of using low temperatures.

Within the scope of this study, the performance and usability evaluations of additives developed from existing and newly produced WMA additives have been made. Specifically, the additives in this study have been used for the first time. This study with the new additives proved that there is no need to change the bitumen ratio.

In Section 2, the bitumen and materials are given as detailed in Fig.1 and Tab.1. Section 3 is related to experimental methods such as viscosity, the softening point and penetration tests that were performed on the bitumen with the additives used in the study. Then, the Marshall Stability test was performed in line with the results obtained. In section 4, the bitumen viscosity of the WMA additives was examined according to the reference bitumen, and the difference in the mixing temperature was observed. The Marshall Stability test was used to measure the values of the WMA-added samples within the ranges specified by the local standards. In the last part, HMA and WMA are compared in terms of the additive costs and energy savings. Section 5 is the discussion and conclusion of the study.

2 MATERIALS

2.1 Bitumen and Additives

According to the Turkish national standards, the recommended bitumen grades for the province where the study was conducted were chosen as 4.2% and 4.8% with a 50/70 penetration for the binder and surface courses. The additives used in this study were determined as “A”, which is an amidoamine derivative and polyamine used in the industry and with long-chain aliphatic hydrocarbon content “B”. These two additives are still used in the road industry and are well-known products. Also, three other additives (a) with a hydrocarbon resin and synthetic-based mineral content named “HYR-901”, (b) with atactic polypropylene and polyolefin content named “Lomot”, and (c) elastomer rubber SEBS compound content named “PDL6020” are newly produced and used for the first time (Tab. 1 and Fig. 1).

Fig. 1.1. *A additive*

Fig 1.2. *B additive*

Fig 1.3. *HYR-901*

Fig 1.4. *Lomot*

Fig 1.5. *PDL6020*

Tab. 1 *Additives and their ingredients*

Additives	Ingredient
Base Bitumen A Additive	- Amidoamine derivative and polyamine
B Additive	Long-chain aliphatic hydrocarbon
HYR-901	Hydrocarbon resin and synthetic based mineral
PDL6020	Elastomer rubber i.e. SEBS compound
LOMOT	Atactic polypropylene and polyolefin

Except for additive A, all the additives were added to the bitumen at a rate of 3% by weight. These rates were preferred as a result of considering the suggestions of the manufacturers. Ipek and Sahin determined the most appropriate additive value to be 0.3% according to the bitumen ratio in their study with the A additive (Sahin and Ipek, 2018). For this reason, the additive dosage used in this study was chosen as 0.3% for the A additive. A and B are additives used in the industry. The other additives were produced for this study in a laboratory environment.

2.2 Aggregate

The aggregate properties and proportions used in the experiments are given in Tabs. 2 and 3. Tabs. 2 and 3 also contain the aggregate rates for the binder and surface courses specified in the national standard. The sieve analysis values for the binder layer are shown in Tab. 2 and in Tab. 3 for the surface course. The granulometry curves are shown in Figs. 2 and 3, respectively.

Tab. 2 *Binder layer gradation and specification limits*

Sieve Size mm (in, No)	% Passed	Specification Lower Limit	Specification Upper Limit
25 (1”)	100	100	100
19 (3/4”)	80	80	100
12,5 (1/2”)	65	58	80
9,5 (3/8”)	55	48	70
4,75 (No. 4)	40	30	52
2,00 (No. 10)	30	20	40
0,425 (No. 40)	15	8	22
0,180 (No. 80)	10	5	14
0,075 (No.200)	5	2	7

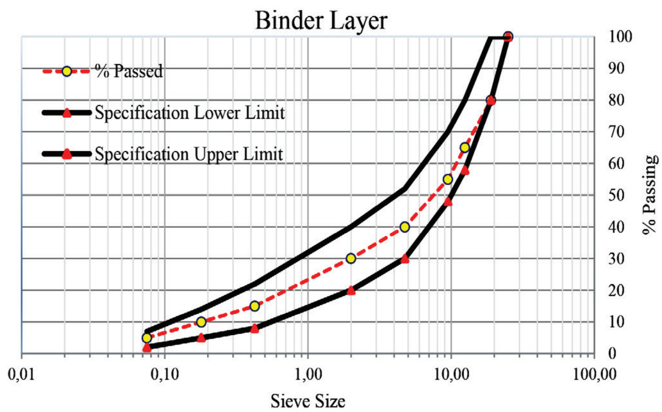

Fig. 2 *Grading curve of used asphalt concrete for pavement binder layer*

Tab. 3 *Surface course gradation and specification limits*

Sieve Size mm (in, No)	% Passed	Specification Lower Limit	Specification Upper Limit
19 (3/4")	100	100	100
12,5 (1/2")	90	88	100
9,5 (3/8")	74	72	90
4,75 (No .4)	45	42	52
2,00 (No. 10)	30	25	35
0,425 (No. 40)	15	10	20
0,180 (No. 80)	10	7	14
0,075 (No.200)	5	3	8

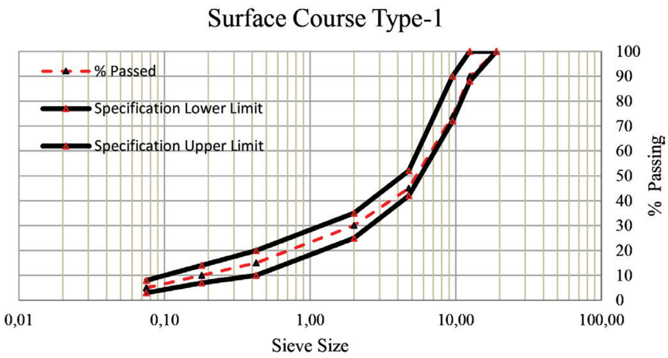

Fig. 3 *Grading curve of used asphalt concrete for pavement surface layer*

3 METHODS

Firstly, the bitumen experiments were carried out in the study. Subsequently, the experiments were conducted on asphalt concrete. The penetration test applied to the bitumen was carried out following the TS EN 1426, and ASTM D5 (2015) standards. The softening point test was carried out according to TS EN 1427 and the ASTM D36 (2015) standard measured the sensitivity of the bituminous binder to the temperature. The viscosity test was performed using a Brookfield Viscometer following the ASTM D4402 and TS EN 2031 standards.

The Marshall Stability test is applied only to WMA using aggregates with a certain penetration or viscosity grade that are 25 mm or less in diameter. The aggregate properties according to the relevant local standard and the type of layer are given in Section 2.2. The aggregates taken from a local province were provided as types of pavements according to the binder and surface course type 1A. In the preparation stage of the samples, the aggregates were initially dried until they reached a constant weight. The amounts of aggregates to be placed in the 1200g specimen was determined according to the mixture gradation. As seen in Section 2.1. the bitumen rate was determined to be 4.2% for the binder layer and 4.8% for the surface course. The experiments were performed by producing three samples for each layer and each additive for the WMA production. Following the TS EN 12697-34 standard, the performance analysis was conducted on the binder and surface courses by considering only the stability and flow values.

4 EXPERIMENTAL TEST RESULTS AND ENERGY-COST ESTIMATE

4.1 Bitumen Test Results

The test results were determined as 7.5 g for the 3% dosed B, HYR-901, PDL6020, and Lomot additives and 0.75 g for the 0.3% dosed A additives. The samples were prepared by mixing them at 180°C for 30 minutes. In addition to the softening point and penetration values of the bitumen, the viscosity values were checked at the temperatures specified in Tab. 4. The experimental results obtained are given in Tab. 4 and Figs. 4, 5, and 6.

Tab. 4 *Bitumen test results*

Additives	Softening Point °C	Penetration 25°C (0,1xmm)	Viscosity 110°C (Cp)	Viscosity 135°C (Cp)	Viscosity 150°C (Cp)
REF A additive	50 50	55 46	2450 2060	562 455	278 224
B additive	83	35	1870	370	188
HYR-901	47	81	1700	376	198
PDL6020	51	67	2120	550	260
LOMOT	52	60	2390	584	303

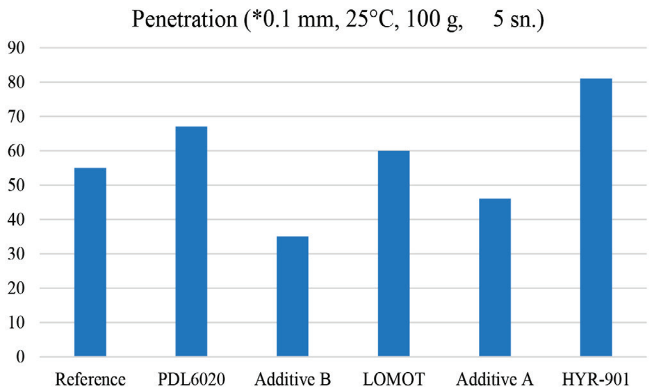

Fig.4 *Penetration test results*

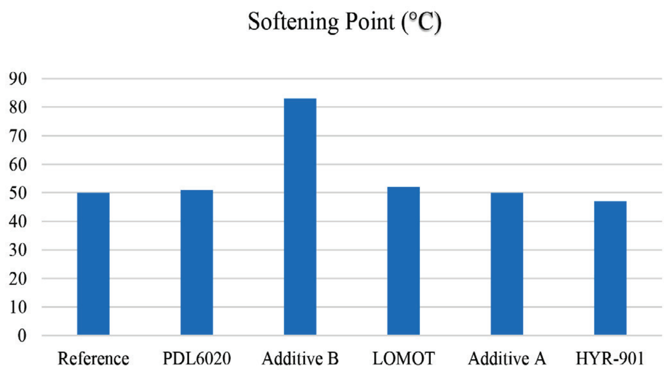

Fig. 5 *Softening point test results*

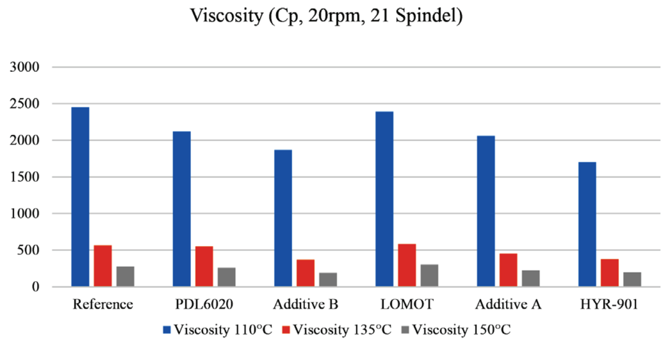

Fig. 6 *Viscosity test results*

The B additive increased the softening point by 66%, while HYR-901 decreased it by 6%; the other additives did not significantly change. As to the penetration values, HYR-901 increased by 47.27%, PDL6020 by 21.82%, and Lomot by 9.1%. The use of the B additive decreased the penetration value by 37.37% and the A additive by 17.37%.

All the additives decreased the viscosity values proportionally at 110°C. These rates were 30.16%: HYR-901, 23.67%: B contribution, 16.9%: A contribution, 13.47%: PDL6020, and 2.45%: Lomot, with the least impact, respectively. The PDL6020 reduced the viscosity value to 135°C with the 34.17% B additive, 33.1% HYR-901 and 19.04% A additive, but the other additives increased the Lomot by 3.91% and 9%.

At 150°C, the PDL6020 showed 6.5%, and almost similar value to the reference sample. The B additive with 32.38%, HYR-901 with 29.8%, and the A additive with 19.43% decreased the viscosity values.

It is predicted that the B, HYR-901, and A additives from the Warm Mix Asphalt additives will be quite economical and provide energy savings due to reducing the temperature and extending the manufacturing season. Additionally, it can be said in line with the values obtained that WMA will benefit in terms of its applicability and workability in the construction field. Based on this situation, the B and HYR-901 additives appear to be usable at a maximum of 135°C, while the A additive seems to be usable at a maximum of 140°C. For this reason, these three additives have been chosen in terms of the use of asphalt concrete in binder and surface courses. The reason for not using all the additives as mentioned before is that the other two additives were not appropriate for the further tests. For this reason and according to the standards, tests were not undertaken for those specimens.

4.2 Marshall Stability Test Results

The reference bitumen sample and aggregates were heated to 160°C and mixed in a heated mixer. The samples were prepared as three specimens, belonging to a group, and their averages were considered. The Marshall Stability test results of these prepared samples for the binder layer are given in Fig. 7 and Tab. 5.

Tab. 5 *Marshall stability test results binder layer*

Sample	Bitumen Rate (%)	Temperature	Marshall Stability (kN)	Flow (mm)
Reference	4,2	160°C	9,62	7,65
A additive	4,2	140°C	10,81	3,53
B additive	4,2	135°C	11,99	3,83
HYR-901	4,2	135°C	12,17	4,42

The Marshall Stability and flow values for the binder layer are shown in Fig. 7.a. and 7.b. The highest Marshall stability value was the HYR-901 added binder layer. The lowest expected flow value was shown by A added to the binder layer. As a result of the experiments, it was observed that the stability values of all the samples are above the local standard (TS EN 12697 – 34). However, the flow values of the reference sample were measured as 7.65 mm and were above the standard value of 4 mm.

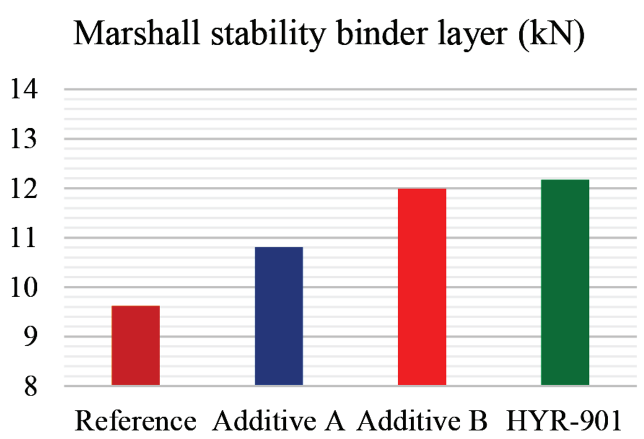

Fig. 7.a *Binder layer Marshall stability values*

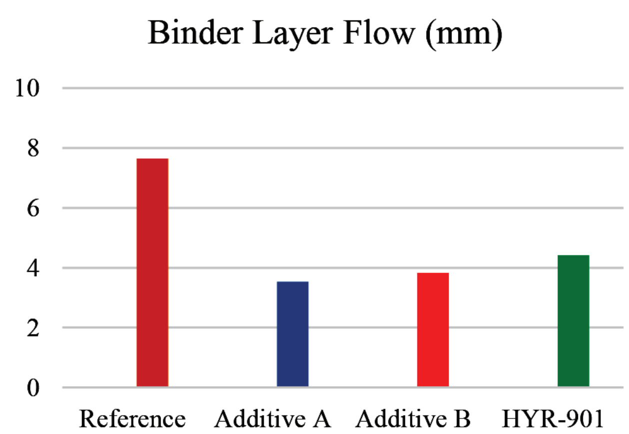

Fig. 7.b *Binder layer flow values*

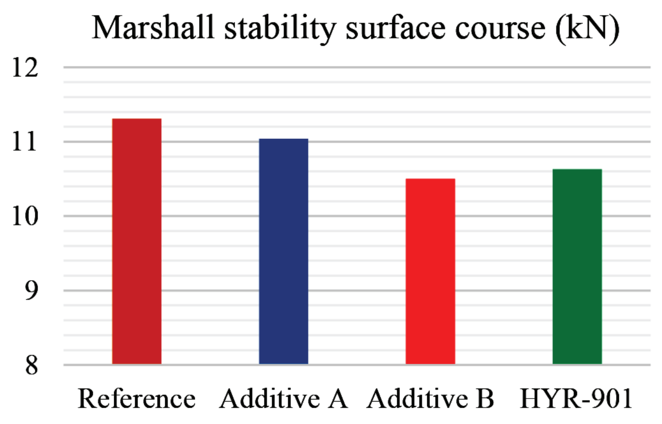

Fig. 8.a *Surface course Marshall stability values*

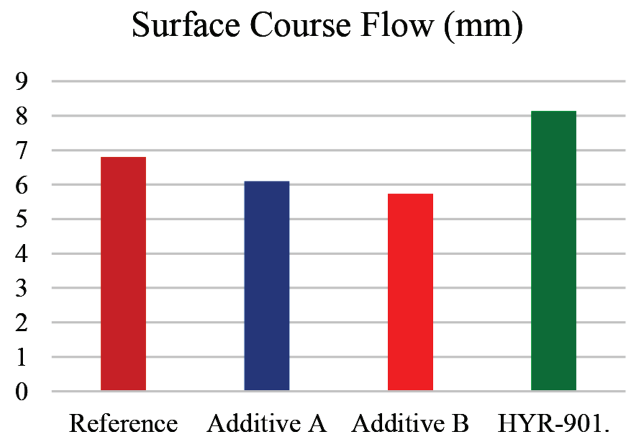

Fig. 8.b *Surface course flow values*

The average of the Marshall Stability and flow values for the surface course are shown in Figs. 8.a. and 8.b. and Tab. 6. The reference sample has the highest stability value. Additive A showed the best strength among the surface course asphalts produced with additives. In terms of the flow values, the surface course asphalt with the B additive showed the best performance.

Tab. 6 *Marshall stability test results surface course*

Sample	Bitumen Rate (%)	Temperature	Marshall Stability (kN)	Flow (mm)
Reference	4,8	160°C	11,31	6,80
A additive	4,8	140°C	11,04	6,10
B additive	4,8	135°C	10,50	5,73
HYR-901	4,8	135°C	10,63	8,13

According to the average values obtained as a result of the experiments, it was seen that the stability values of all the samples were above the local standards. However, the flow values of all the samples were outside the local standard. The additive B sample provided the closest flow value to the standard. Among the stability values, the reference sample showed the best performance. Nevertheless, they achieved the specified values in the additive samples. It is predicted that the samples with additives can be evaluated and used due to the low-temperature factor. Additive A gave the best results in terms of the stability value, and the B additive gave the best results in the flow values. The samples subjected to the experiment are shown in Fig. 9.a., and the appearance of the sample in the mixer that was not successfully mixed at 135°C is shown in Fig. 9.b.

4.3 Energy-cost estimate

As a result of the tests performed for the Binder and Surface courses, it has been shown that the asphalt concrete can be produced at low temperatures with additives. The 25°C decrease in Additive A obtained in the mixture temperature can make asphalt usable even when the weather is not rainy, by showing a positive effect in terms of its workability and operability, and by reducing bad gas and odor emissions. This could be particularly beneficial in terms of energy efficiency. The efficiency calculations were made with the information received from the ECO 4000 Benninghoven module plant manufacturer, as shown in Fig. 10 in the Asphalt Site. In addition to these efficiency calculations, the costs of the additives are also compared. The consumption data regarding the ECO 4000 Benninghoven are given in Tab. 7.

Fig. 9.a *Marshall Specimen*

Fig. 9.b *Not mixed specimen without additive*

Tab. 7 *Plant energy consumption (electricity) data for asphalt production*

Quantity and Temperature	Energy (Electricity) Expended	Energy Saving (for 25°C decrease)	Energy Expended as a Result of Savings
1 t Asphalt	2,5 - 3,5 kWh	%13,5	2,16- 3,02 kWh
160°C for 1 t Asphalt (Aggregate 952 - 958 kg)	74 kWh	%13,5	64 kWh
160°C for 1 t Asphalt (Bitumen 42 - 48kg)	74 kWh	%13,5	64 kWh

Fig. 10 *ECO 4000 Benninghoven module plant*

The costs in the calculations are for May 2022. The energy consumed in heating the aggregates and bitumen for the production of 1 ton of asphalt, according to the data received, is approximately a 13.5% savings in energy provided by a 25°C decrease in the temperature. The energy unit cost was determined as 0.17 $/kWh, including tax. Based on this unit cost, calculations were made by taking into account the fact that the asphalt site produces an average of 100 tons/hour. These calculations again provide an average energy saving of 174$ per 100 tons during one hour of production as can be seen in Tab. 8 for the binder and surface course on average according to the production of HMA and WMA on an hourly basis. These values will provide savings even when considered annually. As can be seen in Fig. 11, the difference in average energy costs over the HMA and WMA is presented, and these values are calculated for over 100 tons per hour. The calculations were made taking into account the unit prices of the additives from the values obtained from the energy savings. The amount of bitumen required for 100 tons of asphalt production is 4200 kg for the binder layer and 4800 kg for the surface course. The required additive amounts and costs are given in Tab. 9 for the binder layer and Tab. 10 for the surface course.

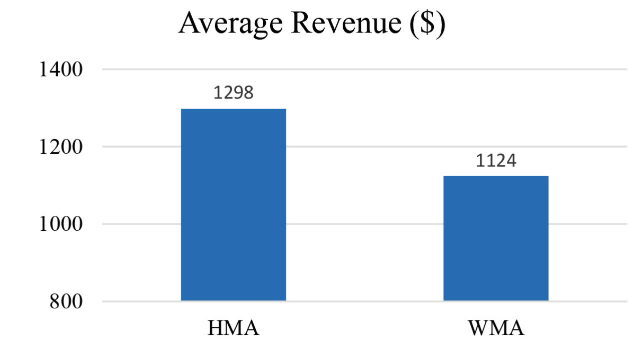

Fig. 11 *HMA and WMA energy cost comparison*

Tab. 8 *HMA and WMA energy costs*

Production Method	100 t/s Asphalt Cost	100 t/s Heating Cost (Aggregate)	100 t/ Heating Cost (Bitumen)
HMA	50,62 $/h	1191 $/h	56,2 $/h
WMA	43,76 $/h	1030,62 $/h	48,5 $/h

Tab. 9 *Binder layer additive costs*

Additives	Bitumen Amount (kg)	Additive Rate (%)	Additive Amount (kg)	Additive Unit Price ($)	Additive Cost ($)
A additive	4200	0,3	12,6	2,60	32,76
B additive	4200	3	126	3,71	467,46
HYR-901	4200	3	126	1,3	163,8

Tab. 10 *Surface course additive costs*

Additives	Bitumen Amount (kg)	Additive Rate (%)	Additive Amount (kg)	Additive Unit Price ($)	Additive Cost ($)
A additive	4800	0,3	14,4	2,60	37,44
B additive	4800	3	144	3,71	534,24
HYR-901	4800	3	144	1,3	187,2

In terms of energy savings, the hourly additive costs for 100 tons of asphalt were taken into consideration and given in Fig. 12. It was determined that the largest cost gain belongs to the A additive, depending on both the usage rate and the unit price. The B additive increases the cost considerably due to the unit cost.

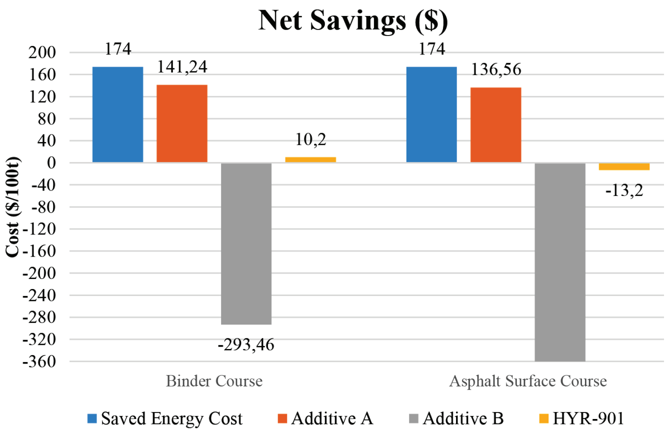

Fig. 12 *Energy savings and additive costs*

The savings value shown in blue in Fig. 12 should be evaluated as the amount gained from the asphalt production in the case of a 25°C decrease. Compared to the cost of the additives, although the B additive is the highest cost (Tab. 9), it provides fewer savings due to the high unit cost. The A additive provides the lowest cost since the contribution rate is low. However, when the A additive is used, the maximum temperature reduction is approximately 15°C, which increases the energy costs shown above, compared to 25°C. In this case, the HYR-901 is a highly preferable additive as it saves 10.2$ per hour for 100 tons of asphalt production for the binder layer, depending on the viscosity. Due to its ease of production, environmental impact, and cost, the HYR-901 can be a preferable addition to WMA technology.

5 DISCUSSION AND CONCLUSION

In this study, the performance evaluations of the WMA additives were made based on the specifications. These evaluations were tested on the binder and surface course, which is preferable more in terms of traditional asphalt use, and compared according to the Marshall Stability values after the use of the additive ratios.

In the laboratory, the experiments were performed by adding 50/70 penetration bitumen and a WMA with A, B, LOMOT, PDL6020, on HYR-901 additive. As a result of these experiments, additives that can provide low-temperature production in terms of viscosity were determined and preferred according to their suitability for asphalt concrete production. The additives and bitumen rates were used to prepare Marshall test specimens for A, B, and HYR-901, which include one new product and two known products for the surface course and binder layers. These specimens were compared with the reference sample to examine the performance values of the additives at low temperatures.

As a result of the modifications made with the 50/70 penetration bitumen WMA additives, it has been observed that each additive affects the properties of bitumen differently:

- Since the penetration value is inversely proportional to the viscosity, as the penetration increases, the bitumen softens; the higher the viscosity, the harder the bitumen. Since the viscosity of bitumen with very high softening points is also high, their production temperatures are also high. It was observed that the A and B additives decreased penetration, while the other additives (HYR-901, PDL6020, and Lomot) increased it. It was observed that the A additive did not change the softening point value; the PDL6020 and LOMOT increased it slightly, and the HYR-901 decreased this value a little. The B additive increased the softening point value by 65%.
- Since the performance of these additives was evaluated according to the bitumen ratio used, the efficiency required has been achieved without any change in the bitumen ratio. The fuel savings, energy efficiency, and increase in the workability of the mixture at low temperatures will reduce the harmful effects on the environment and will provide positive effects on the health of workers.
- The energy savings from the asphalt production are calculated as an average of 174 $/h. When the unit costs of the additives compared to this amount are examined, at a temperature difference of 25°C, the HYR-901 additive for the binder layer has a profit of 10.2$/h for 100 tons of asphalt production.
- The values obtained as a result of the viscosity tests show that the A and HYR-901 additives have better capacity for the reducing temperature. In particular, the HYR-901 additive might be used in cold climates. It was observed that the production temperatures of WMA prepared with these additives (A, B, and HYR-901) decreased by 20-30°C. This decrease in the mixture temperatures not only saves fuel but also means a reduction in harmful gas emissions in the production plant.

As a result of the Marshall tests performed on the surface course and binder layer, it has been seen that it can be very beneficial to use additive mixtures for the production of WMA in terms of strength and stability. Also, this study shows the new WMA additive products are very beneficial and performed well compared with the others. At this time, preferring WMA and similar technologies will be beneficial as they are economical and environmentally friendly.

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sciendo
Slovak Journal of Civil Engineering
Vol. 31, 2023, No. 1, 45 – 51
DOI: 10.2478/sjce-2023-0005

A NEW PERSPECTIVE ON RESIDENTIAL BUILDING VENTILATION FROM THE POINT OF VIEW OF ACHIEVING THE DESIRED INDOOR AIR QUALITY USING DIFFERENT VENTILATION SYSTEMS

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Abstract

The case study analyses a specifically described situation from the present and a summary of events from the past, finds alternative solutions, and decides on one of them. The target of such a detailed analysis was a concrete apartment building, which was still in the project phase; the efforts to change its proposed air conditioning system to a more energy-efficient one are the subject of the case study. Apartment buildings with modern technology installed in terms of sanitary equipment, heating, and simple methods of ventilation and cooling do not constitute part of the project.
Through a detailed analysis of the calculation of the heat losses through ventilation in the case of local and decentralised ventilation applied to one apartment unit, this failure to address modern solutions is remedied.

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Key words

- Mechanical ventilation,
- Local ventilation,
- Centralized and decentralized system of ventilation,
- Heat recovery unit,
- Heat losses,
- Thermal load.

1 INTRODUCTION

The current energy crisis again forces people to think about how and where to save energy of any kind. However, the proposed solutions do not always go hand in hand with the creation and long-term maintenance of the quality of the indoor environment. Heating, ventilation and air conditioning (HVAC) have some of the biggest impacts on indoor air quality. If a good choice in favor of forced ventilation occurs, it is often spoilt by the choice of the wrong type of air conditioning system or the wrong choice of the distribution elements themselves. A big plus in the design of apartment buildings is the fact that an air conditioning project not only deals with the usual under pressure ventilation of sanitary rooms and the connection of steam and moisture to the central exhaust pipe, it also addresses the replacement of degraded air with fresh outdoor air in the living spaces by a central or decentralised system. Each has its advantages and disadvantages, but in general it can be concluded that both are suitable and are not very investment-intensive in terms of the total construction costs. What is decisive at the end of any project are the operating costs, which will be discussed at the end of this study. For the design of the forced ventilation of housing units in residential buildings, we have several types of air conditioning systems at our disposal, which will be briefly discussed in the following sections.

2 CONTROLLED VENTILATION WITH THE PARTIAL MODIFICATION OF THE OUTDOOR AIR

The driving force for the design of forced ventilation in apartment buildings has been given by the new requirements defined in the Decree of the Ministry of Internal Affairs and Communications of the Slovak Republic No. 364/2012 Coll., which stipulates that residential buildings built after 2015-01-01 must achieve energy class A1 and, from 2020-12-31, must achieve energy class A0 in primary energy consumption. One of the many solutions offered for the technical equipment of buildings as a whole, the achievement of class A0 in the field of air conditioning is represented by a controlled forced ventilation system with partial treatment of the outdoor air through the application of an air conditioning unit that uses energy from waste air in the form of heat recovery. Basically, these are ventilation units with recuperative or regenerative heat exchangers.

2.1 Central air conditioning system

A central ventilation system (Fig. 1) is made up of one or more air conditioning units, which zonally adjust the air for apartments with approximately the same heat load values. They are mostly located on the roof of a building or in its technical spaces and ensure the common ventilation of apartments located above each other. The apartments are connected by a common vertical shaft with air ducts and are separately designed for the supply of outdoor air (ODA) and the removal of degraded air (EHA). To ensure the individual ventilation of these apartments according to the immediate requirements of their users, a volumetric air flow regulator is installed at the entry and exit point of the air duct of each apartment (Horák et al., 2014).

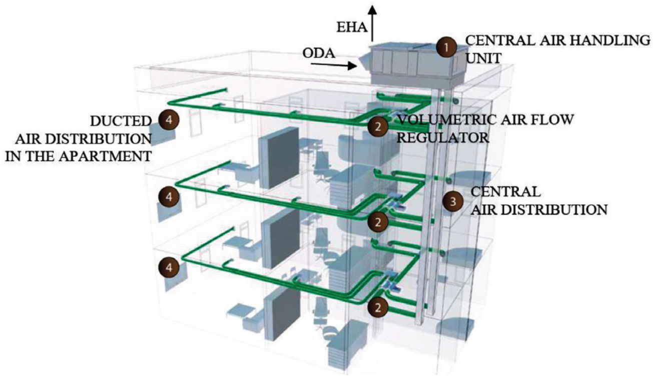

Fig. 1 *Scheme of the central air conditioning system for an apartment building (Atrea, Ltd.)*
ODA – outdoor air supply, EHA – exhaust air outlet, 1 – central air handling unit with heat recovery (located on the roof or in the basement of an apartment building), 2 – volumetric air flow regulator (located in an apartment under the ceiling), 3 – central air distribution connecting the central air conditioning unit and the regulator, equipped with noise dampers, 4 – ducted air distribution in the apartment

The conditioned outdoor air in the air handling unit is distributed to the living spaces, such as the living room, dining room, bedroom, or children's room; the air extraction is from the kitchen, bathroom, toilet, or from a closet. The volume air flow regulator has the task of ensuring the regulation of the air exchange or ventilation efficiency in the apartment. It is possible to use manual or automatic controllers combined with the indoor air temperature and relative humidity sensors or carbon dioxide CO_2 sensors. The air performance of the central air handling unit is thus permanently adjusted in order to achieve and maintain optimal environmental conditions for people in the indoor environment, but at the same time ensure the lowest possible energy consumption of any kind (Kajtár and Kassai, 2010). The great advantage of this system is that it provides controlled ventilation using recuperation, i.e., with the use of heat from the exhaust air, which in the cold seasons of the year is used to preheat the cold from frosty outdoor air and, conversely, in the warm seasons of the year, to precool the warm to hot outdoor air. The mutual separation of these two streams of external and exhaust air in the plate recuperative enthalpy exchanger creates a suitable quality of the supplied air with a sufficient temperature and humidity, without any dustiness of the indoor environment and with the reduction of possible odours in the rooms (Domnita and Kapalo, 2019).

2.2 Decentralised air conditioning system

A decentralised air conditioning system is based on the principle that a small air conditioning system (ventilation) is placed in each apartment unit, which thereby ensures controlled ventilation of the apartment with heat recovery. It is usually located under the ceiling in the entrance corridor to the apartment (hallway), from where the supplied air is led through the under-ceiling distribution to the various rooms using internal distribution elements such as nozzles with a long range of air flow, plate valves or rectangular two-row outlets with volume flow regulated air. Air extraction is from the hygienic rooms and the kitchen. The supply of outdoor air and the discharge of waste air can be solved in two ways. The first method, the so-called central method, i.e., involves a common supply of outdoor air (ODA) and the discharge of exhaust air (EHA) to the outdoor environment, for all the apartments located above each other. These two air ducts are led through a common installation shaft with an outlet on the roof of the apartment building (Fig. 2).

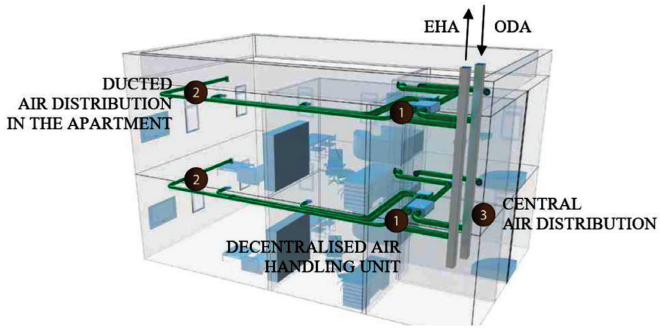

Fig. 2 *Scheme of a decentralised air conditioning system for an apartment building with a central supply of outdoor air and an exhaust of degraded air (Atrea, Ltd.)*
ODA – outdoor air supply, EHA – exhaust air outlet, 1 – decentralised air conditioning unit with heat recovery (located in the entrance area of the apartment), 2 – apartment air distribution, 3 – central air distribution connecting the decentralized air conditioning units in the apartments above each other

The second external air supply and waste air extraction method consists of its intake (ODA) and exhaust (EHA) through the perimeter wall of the relevant apartment (Fig. 3). In this case, however, it is important to pay attention to the correct location of the intake and exhaust openings both in relation to the opening structures (windows, balcony doors) and in relation to each other. If the opening (equipped with a rain louver) is too close to the opening intended for blowing the waste air and if specific random weather conditions occur, already degraded air with pollutants could be sucked back in, which would of course be undesirable.

2.3 Local ventilation system - unit ventilation device

Local recovery units are located in each living room (Fig. 4) and bring fresh outdoor air directly through the perimeter wall

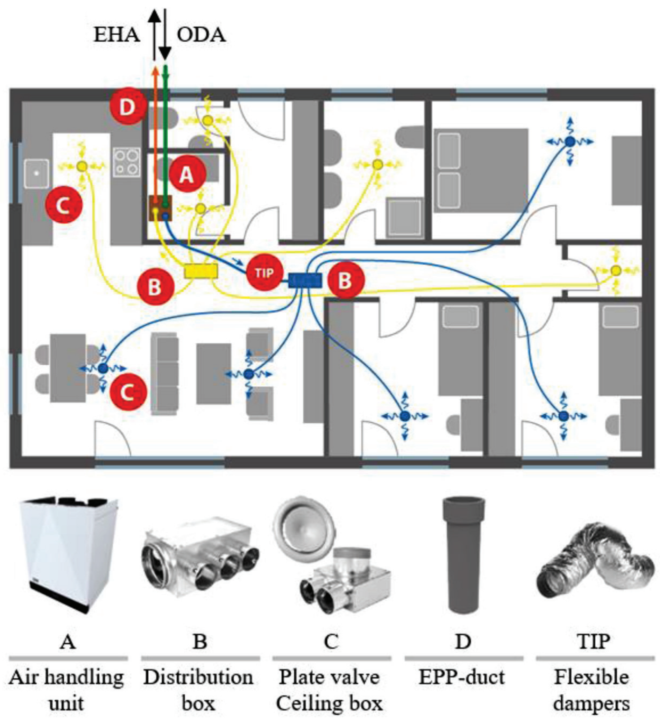

Fig. 3 *Scheme of a decentralized air conditioning system for an apartment building with a supply of outdoor air and the removal of degraded air within the housing unit (Multivac, Ltd.)*
ODA – outdoor air supply, EHA – exhaust air outlet

into the interior space. These systems are especially suitable for renovations as they do not require any major structural modifications.

The ventilation unit itself (Fig. 5) is a device whose main function is the continuous supply of outdoor air to living spaces while simultaneously removing waste air. It can work in up to four operating modes:

– automatic passive ventilation - open blind, fan is switched off,

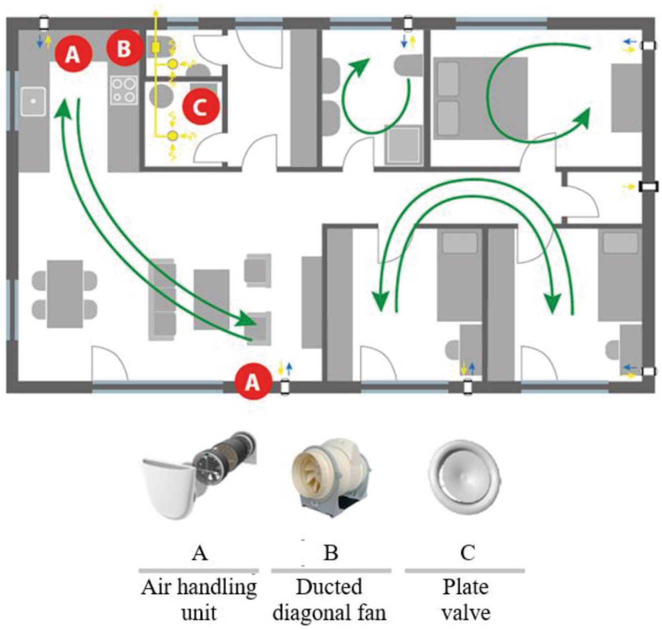

Fig. 4 *Scheme of the air handling system for an apartment building using local ventilation units (Multivac, Ltd.)*

– air supply, supply of fresh outdoor air to the room,
– ventilation - extraction of degraded air from the room or the supply of fresh outdoor air to the room, depending on the setting of the unit. The ventilation mode works effectively when two or more units are connected in a series. In this mode, half of the units provide the air supply, and the other half provides air extraction, depending on their settings,
– ventilation with heat recovery - cyclical alternation of the direction of the air flow in 70 second intervals.

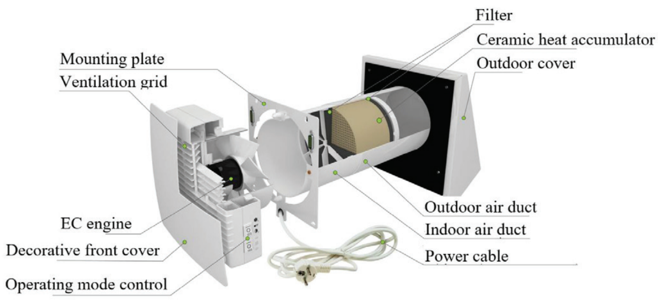

Fig. 5 *Local ventilation recovery unit (Kama, Ltd.)*

The description of the operation of the unit consists of the alternation of two operating cycles: Cycle I - heated air is extracted from the room, which heats the heat accumulator. After being heated, the ventilation unit automatically switches to the air supply mode (Cycle II). Cycle II - Fresh air is brought into the room, which is warmed by the heat captured in the thermal accumulator. After it cools, Cycle I is repeated.

This method of mechanical ventilation, which was proposed in the original air conditioning project of the apartment building, became the subject of this case study.

3 ANALYSIS OF THE PROJECTED STATE OF THE HOUSING UNITS

The subject of the case study is a multifunctional residential building (Fig. 6) in Slovakia with 98 residential units and an estimated population of 211; it consists of parking spaces, storage spaces, and the technical facilities of the building on an underground floor. The entrance and the non-residential, commercial, and administrative spaces are located above-ground on the first and second floors. The apartment units are located on the third to eighth floors, with smaller apartments

Fig. 6 *View of the multifunctional apartment building from the inner block (Penta Real Estate, Ltd.)*

facing one side of the building and larger apartments facing the inner block. The building is built to a standard that meets the requirements for class A0 energy certification.

As to the ventilation of the apartments, the designer considered a negative pressure ventilation method, consisting of an element of the entrance facade and exhaust fans. The designer started that the amount of outdoor air was determined according to the standard STN EN 16798-1:2019, or based on the requirements set out in the Decree of the Ministry of Health of the Slovak Republic No. 259/2008 Coll. for the required amount of outdoor air per person (20 to 25 m^3/h) and a minimum exchange of outdoor (fresh) air for living spaces (0.5/h).

To ventilate the living spaces, acoustic ventilation slits are used with suction brought out to the lining of the facade opening for better visual and cleaner effects with a location above the heating elements to ensure the air heating. The air extraction is planned to occur from the hygienic areas of the toilets, bathrooms, and chambers using two-stage radial exhaust fans that will lead out through a riser pipe above the roof of the building to the outdoor environment. A fan will always run, and turning on the lighting will increase its power. Part of the project documentation submitted was the calculation of the heat losses, where the calculated value of the heat losses through ventilation, in the case of the negative pressure method of ventilation, was cca 81.4 kW, which represents 45 % of the total heat losses of the building (Tab. 1).

Tab. 1 *Proportion of heat losses and proposed heat output – negative pressure method of ventilation*

	Heat loss by heat transfer	Heat loss by ventilation	Heat Input for heating	Total proposed heat output
Apartment Building (98 flats)	75,667 W	**81,439 W**	23,566 W	180,672 W
	42 %	**45 %**	13 %	100 %

The share of heat losses from ventilation with the negative pressure method of ventilation represents a 45 % share of the total proposed heat output of the apartments (Fig. 7).

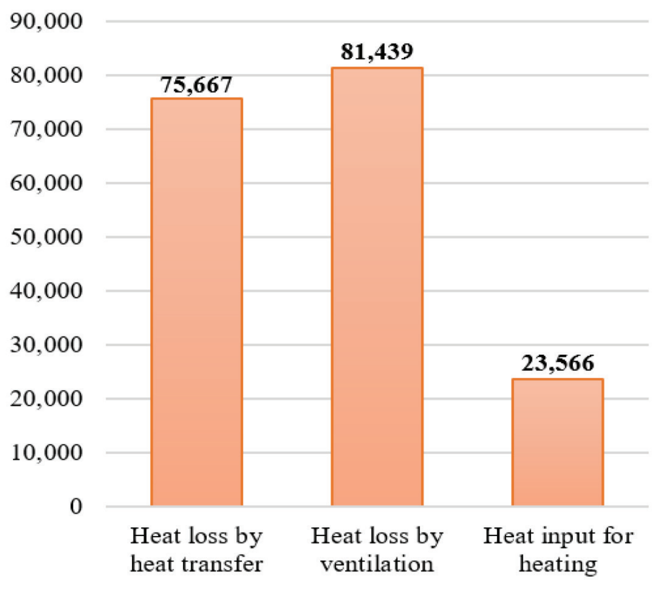

Fig. 7 *Proportion of heat losses and proposed heat output*

This method for the ventilation of apartments could be identified as a weakness of the project. The fact that the air conditioning project is considering negative pressure ventilation in the new building is insufficient. Even the minimum intensity of the air exchange of 0.5/h, which represents the minimum health requirement, and neither the air exchange rate of 0.6/h for building category II. – apartment buildings according to STN EN 16798-1:2019.

The designed radial fans have a shutdown function called the "zero degree"; in the case of a shutdown, no air exchange will be ensured. With natural and unregulated ventilation through the windows, we also will not reach a minimum air exchange rate, unless the building has sufficient air permeability. It would have to be ventilated every 10 minutes to ensure fresh air doses and optimal CO_2 values. Building category II has optimal values of CO_2 – 800 ppm. During the night in unventilated rooms, CO_2 values can reach up to 3000 ppm, which can cause fatigue, lack of sleep, etc. At the same time, with both natural and mechanical negative pressure ventilation in the cold months, significant heat leaks could occur, which would make up a significant part of the building's total heat losses.

4 OPTIMISATION OF THE PROJECT SOLUTION – THE DESIGN OF VENTILATION WITH HEAT RECOVERY

Although the building meets the conditions to achieve energy certification in class A0, it is recommended to solve the ventilation of the apartments with heat recovery to achieve savings in thermal energy to cover heat losses through ventilation and, at the same time, to ensure air quality in the apartments.

4.1 Legislation

The basic document in the legislation, which sets the minimum exchange of outdoor air per hour per person present, is the Decree of the Ministry of Health of the Slovak Republic No. 256/2008 Coll., where the air exchange is determined based on the volume of the room per person while the rooms are free of sources of harmful substances and people with minimal movement activity, which corresponds to a minimum air exchange intensity of 0.5/h. At the same time, the decree states that, for health reasons, the total minimum air flow during occupancy should never be less than 4 l/s per person, which also corresponds to the indicated intensity of the air exchange.

To evaluate the energy criteria of buildings, the standard STN 73 0540+Z1+Z2:2019 also stipulates a minimum air exchange of 0.5/h. For air quality assessments, we use the standards STN EN 16798-1:2019 and STN EN 15665:2010, which are based on the assumption that users should be satisfied with air quality immediately after entering a room, i.e., before entering the room, they are already adapted to the air. The EN 16798-1:2019 standard defines air quality categories with regard to CO_2 values. This standard should be considered when designing in polluted urban areas, as the levels of CO_2 and NO_x can be higher than elsewhere. Local standard STN 73 0540-2+Z1+Z2:2019 and the Decree of the Ministry of Health of the Slovak Republic No. 259/2008 Coll. set out minimum air exchange requirements, and the standard also extends energy requirements to achieve Net Zero targets based on reference values and the building shape coefficient. The standard STN EN 15665:2010 defines the nominal flow rates of the supplied and extracted air, which are similar to those in other EU countries.

4.2 Air flow volume calculations

When determining the volume flow values necessary for recovery units, standard STN EN 16798-1:2019 is used to ensure a minimum air exchange rate of n = 0.6/h for category II, i.e., apartment buildings, and at the same time, to ensure the volumetric flow rates of exhaust air from humid areas (kitchen, bathroom, WC or utility room): kitchen: 11.1 l/s (40 m^3/h), bathroom: 11.1 l/s (40 m^3/h), WC: 5.6 l/s (20 m^3/h), living room: 8.3 l/s (30 m^3/h) and bedroom: 8.3 l/s (30 m^3/h). The resulting air volume flows are shown in the following table (Tab. 2).

As an alternative to this project, we chose a decentralized recovery solution with an enthalpy exchanger in the ceiling design; the specific type of unit is WAFE 210 E for small apartments. Large apartments must be equipped with two WAFE 201 E units or a higher row of WAFE 350 ERV units. The fresh air intake and the exhaust of the degraded air exhaust will occur above the roof of the building. The units will be placed on the lower soffit of the sanitary facilities. If the apartment has a separate bathroom from the toilet, it is preferable to place the unit in the toilet. Non-return valves, thermoflex pipes, or plastic pipes will be installed to connect the recuperation unit from the riser on the branches of the risers. Plenum boxes will be connected to the recovery unit by pipe silencers to eliminate noise. With the proper assembly of the units, the noise levels will be maintained in accordance with the hygiene regulations (Šikula et al., 2018).

4.3 Heat losses by ventilation after passing through an enthalpy exchanger

According to the standard STN EN 12831-1:2019, the heat losses form the relationship for the calculation of heat losses through ventilation. The outdoor temperature calculated is replaced by the temperature of the air supplied after passing through the device with heat recovery, but without active preheating. An estimation of the temperature of the supply and exhaust air after passing through the heat recovery is made from the relevant ventilation design, and all the parameters refer to external calculation conditions. The temperature of the air supply can only take into account the increase in temperature through heat recovery and does not take into account the increase in temperature from active preheating (Vargová et al., 2021; Kumar et al., 2022; Li et al., 2022).

In this calculation of the heat losses, where the calculated value of the heat losses through ventilation, in the case of the ventilation system with heat recovery, was cca 12.9 kW, which represents only 13 % of the total heat losses of the building (Tab. 3).

In the case of ventilation with heat recovery, the share of heat losses through ventilation in the total proposed thermal performance of the apartments was significantly reduced, i.e., a share of 13 % (Fig. 8).

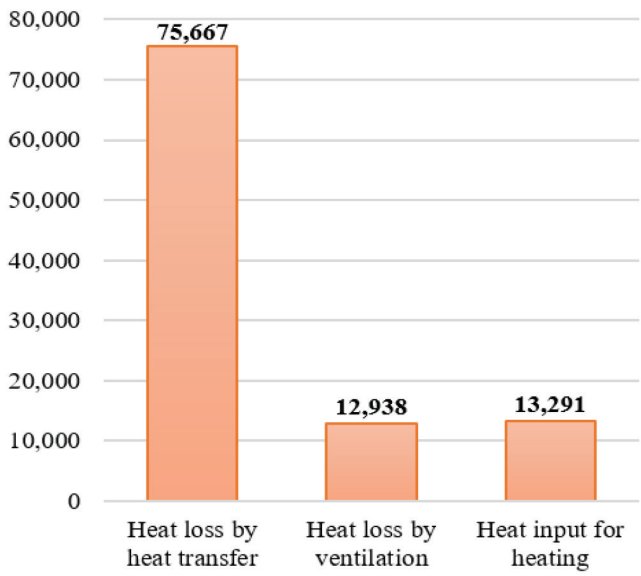

Fig. 8 *Proportion of heat losses by a ventilation system with heat recovery*

Tab. 2 *Volume flow designs for apartments – supply/exhaust*

Type of apartment	1st level of operation (minimum air exchange)	2nd level of operation (nominal - hygienic dose of air)	3rd level of operation (maximum intensive ventilation)
	Air flow volume (m^3/h)		
$1^{1/2}$ rooms	25	60	90
2 rooms	30	80	120
3 rooms	50	120	180
4 rooms	60	160	240

Tab. 3 *Proportion of heat losses by a ventilation system with heat recovery*

	Heat loss by heat transfer	Heat loss by ventilation with heat recovery	Heat input for heating	Total proposed heat output
Apartment building (98 flats)	75,667 W	**12,938 W**	13,291 W	101,896 W
	74 %	**13 %**	13 %	100 %

Tab. 4 *Total savings on heat losses by ventilation with heat recovery system*

Apartment building (98 flats)	Heat losses by ventilation		**Total savings on heat losses**	Reduction of total heat output of heat source
	Negative pressure ventilation system *(Local ventilation)*	Ventilation with heat recovery system *(Decentralised ventilation)*		
	81,439 W	12,938 W	**68,500 W**	43.60 %

4.4 Effect of heat losses by ventilation on the overall saving of heating energy

The following table shows (Tab. 4) values of overall heat losses caused by ventilation in the case of both ventilation systems: local system represented by negative pressure ventilation system and decentralised system represented by ventilation with heat recovery.

It is obvious that energy saving with respect to heat loss caused by ventilation is in the case of ventilation with heat recovery system by 68,500 W lower than in the case of negative pressure ventilation.

5 CONCLUSIONS

Heat loss has been calculated according to the standard STN EN 12831-1:2019. According to the standard STN 73 0540-3/Oa:2020 the location of the apartment building under construction has the following climatic characteristics: the calculated outdoor air temperature for winter period -11 °C and the indoor air temperature for winter period 20 °C.

Thanks to lower heat losses through ventilation, the total heat output of the heat source will be significantly reduced from the original value of 180,672 W (local ventilation) to the value of 101,896 W (decentralised ventilation), which represents a decrease of 43.60 %.

Despite the fact that the investment costs of the technical solution of decentralised ventilation with under-ceiling units with enthalpy exchangers are higher than in the case of using a under pressure ventilation method with supply facade elements (note: the calculations proving this claim are not the subject of this article), from the point of view of energy savings, it is worthwhile to install a system with recuperation. After a total evaluation of all the input costs, which relate to the purchase price, electricity consumption, heat consumption during ventilation, and service costs for both systems, the investment was obtained within an acceptable payback period.

Acknowledgments

This work was supported by the Ministry of Education, Science, Research and Sport of the Slovak Republic under VEGA grant 1/0303/21, VEGA grant 1/0304/21, KEGA grant 005STU-4/2021, and by the Research and Development Support Agency of Slovakia under project APVV-21-0144.

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DOI: 10.2478/sjce-2023-0006

THE IMPACT OF CLIMATE CHANGE AND REGULATION OF THE WATER REGIME ON THE MORPHOLOGICAL STRUCTURE OF THE FLOODPLAIN FORESTS IN PETRŽALKA, SLOVAKIA

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Abstract

The main landscape-forming component has always been the forests in the lowlands. The devastation and disturbance of forest areas by anthropogenic activity change the ecological conditions in their environment. Climate and atmospheric changes affect the balance of the mutual relationships between individual components, as well as the existence of direct and feedback relationships in forest ecosystems. The transformation of bioclimatic and ecological conditions have caused the degradation of the Pannonian floodplain forest communities in Slovakia. Urbanization in Bratislava has caused the fragmentation of the surrounding forests. With changes in sunlight and heat conditions, floodplain communities are forced to become acclimatized to drier conditions, which lead to morphological and structural changes in their composition.
In this study we examined phytocenological records from 1999 to 2020 from various sources. The survey points to the impact of climate change and anthropogenic influences on biodiversity. The absence of floods and the drying of floodplain forest soils could have caused this change in the species' composition.

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Key words

- Forest morphology,
- Change of water regime,
- Climate change,
- Floodplains.

1 INTRODUCTION

Bratislava, the capital of Slovakia, and its surroundings have undergone many changes throughout their history. The first written mention of the territory of Petržalka, now a large neighborhood in Bratislava, dates from 1225. The first interaction of people with the floodplain biotopes was mainly economic. They used them for logging and hunting wild animals. Historical maps prove the intervention of the inhabitants in the vegetation of the floodplains, from which the transformation of the natural landscape into an economically viable urban region is evident (Reháčková, 2008).

A lack of production and accumulation of humus characterized the soils of the floodplain forests because floods and alluvial accretion disturbed them (Jurko, 1990).

The biotopes have been preserved in a fragmented form among the prevailing urban landscape. In connection with the operation of the nearby Gabčíkovo-Nagymaros dam and waterworks, socio-economic activities continue that still impact the development of biotopes in the area. During the dam´s construction, which began in 1977, a considerable area of these biotopes was devastated. The operation of the waterworks started in 1992. The waterworks disrupted the aquatic regime of the river and disrupted the flood regime and groundwater fluctuations.

The biotopes of the floodplain forests in the urbanized environment of Bratislava are subject to stress factors caused by anthropogenic factors. The development and urbanization of various locations in Petržalka pose the danger of disrupting the ecological stability and the biological balance, which significantly contribute to the fragmentation of the remnants of the Bratislava floodplain biotopes in the area studied.

Climate change, global warming, and the greenhouse effect are affecting the current state of the floodplain forests (Keszeliová et al., 2022). These global changes also impact forest communities in their structural composition or the variability of species in the biocenosis. The high concentration of greenhouse gases in the atmosphere (CO2, CH4, N2O, freon) is associated with human activity, specifically the burning of fossil fuels (Vološčuk et al., 2016).

According to climate change scenarios, biocenoses in lowland areas will be the most affected. Climate change disrupts the balance of the interrelationships of individual components and the existence of direct and feedback links in forest ecosystems (Ružička and Mišovičová, 2006). The increasing CO2 concentration and average temperature, changes in the amount and distribution of precipitation and subsequent changes in the water balance, increasing UV-B radiation, and changes in the frequency and intensity of extreme climatic events directly but also indirectly affect the composition of forest ecosystems (Minďáš and Škvarenina, 2000). Changes in bioclimatic conditions induced the transformation of forest communities along the Danube River.

The causes of the decline in the woody vegetation of floodplain forests and the decrease in the composition of autochthonous species are anthropogenic interventions and the inappropriate regulation of watercourses, which negatively affect surface water regimes and groundwater regimes, causing the absence of natural floods in river floodplains. The construction of roads and the urbanization of Petržalka have led to the fragmentation of its forest habitats. This phenomenon has affected changes in the sunlight and thermal conditions in its floodplain communities.

Plant communities react to the effect of external factors by changing the size of the assimilation organs or by undergoing various growth defects (Hutárová, 2011). These changes in the habitat of different plants are necessary for these biotopes to survive and live with the environment in balance. It is a response to a stimulus to which they have exposed the organism in different time intervals. The tolerance capacity of the species may vary with the factor being influenced (Forman and Gordon 1993).

We can consider floodplain communities as so-called ecotypes. This means that their optimal and tolerance limits correspond to local conditions. The regulation of natural conditions have changed the optimal tolerance limits of species, which have reduced the intensity of the vital activity of species typical of floodplain forests. A lack of production and the accumulation of humus characterize the soils of floodplain forests because floods and alluvial accumulation disturb them. Different textures and varied mineral compositions characterize these soil types. The absence of a natural flood regime has led to an increase in the formation of humus in the soil component, which has violated the limit values in which these biotopes can exist (Troll, 1939).

2 MATERIALS AND METHODS

We formulated a thesis based on which significant degradation of floodplain habitats is assumed in relation to climate change and anthropogenic influence. To determine the changes in the forest morphology and forest composition in Petržalka, we used a methodical procedure, which is based on comparing field data from several time horizons (using a time series of entries). During the selection of the areas monitored, the first step was a survey of the contemporary landscape cover to determine the selection of reference areas. For a survey of the territory, we used various map materials. Then we examined the phytocenological records from 1999 to 2020. These records come from the Joint Annual Reports on the Environment Monitoring (JAREM, 1999 - 2010), freely available biomonitoring data (Biomonitoring.sk, 2013, 2015), and our own field records (2020). All the areas monitored (Fig. 1) are located along the Slovak reach of the Danube. For our own field recording, thirteen reference areas (of approx. 675 m^2) in Petržalka were selected based on detailed analyses to correspond to different forest conditions. These areas are located in an urbanized environment that is cut off from surface water fluctuations. To preserve the homogeneity of the collected data, we also made phytocenological records in the field at the end of October 2020. A typical phytocenological record from the locality of Veľký Zemník (Tab. 1) describes information about the characteristics of the vegetation and the coverage of individual floors, which is important in the synthesis or diagnosis of the typological units.

Unlike Petržalka, all the JAREM and Biomonitoring reference areas (Fig. 1) are located in a natural environment, and some of the localities belong to an area with controlled flooding. With the help of these entries, we evaluated the average coverage of the individual floors in the reference sections of the Pannonian floodplain forests for the years 2000, 2010 and 2020, which helped us create a real picture of the changes in the forest morphology and forest composition.

When analyzing phytocenoses (vegetation), we describe them according to certain characteristic features, thereby resulting in a phytocenological record. The following characteristics are usually evaluated: the floristic composition (set of species), abundance (abundance), coverage (dominance), and sociability and vertical structure (vertical stratification in the biotope) (Križová and Nič, 2012). The area inventoried was measured using the Nautiz X6 GPS receiver and the MAPUJ program, which enabled us to edit the attributes of the individual reference areas and points directly in the field. According to the map analyses, we determined the coordinates of the reference area; they were corrected in the field because of the dense canopy of vegetation. The first step was to mark out the site directly in the MAPUJ application, which was followed by recording the GPS location of individual trees. The accuracy of the device ranged from 1.5m to 3.4m. We evaluated 21 trees in a dense canopy and approximately 9 shrubs. Inaccuracies could have occurred because of an incorrect determination by the ocular method or by different mappers of the percentage of cover.

3 RESULTS AND DISCUSSION

The status of the vegetation at the individual areas monitored was different, which can be attributed to the different locations of the individual sites. The average values of the coverage of the individual plant floors in 2000 can be seen in (Fig. 2).

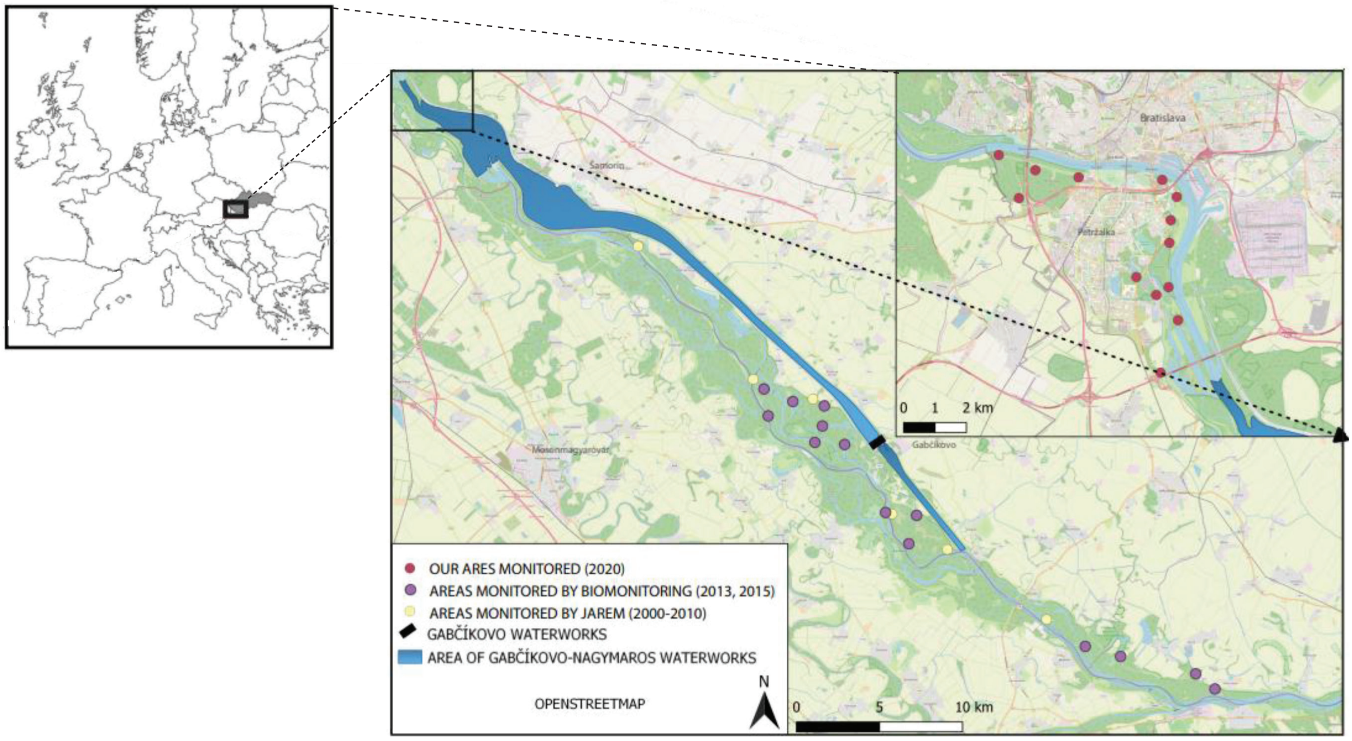

Fig. 1 *map of all the reference areas examined from 1990 to 2020*

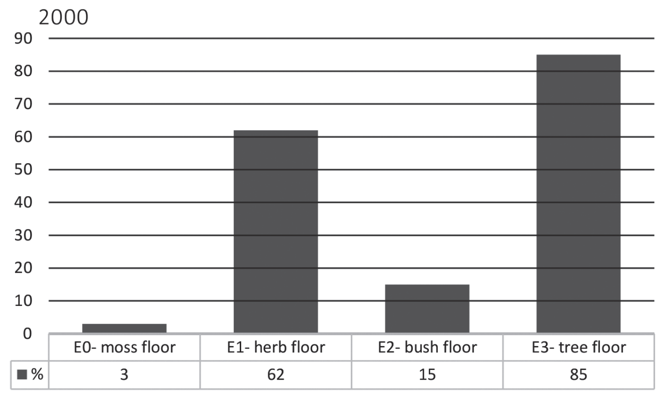

Fig. 2 *Average percentage value of plant floor coverage for the year 2000*

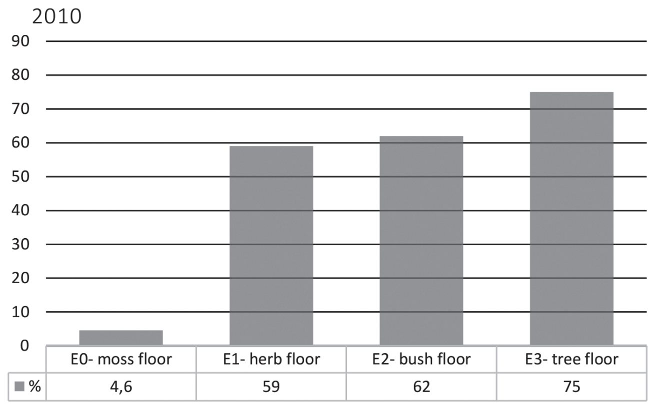

Fig. 3 *Average percentage value of the plant floor coverage for the year 2010*

In 2000, we noted considerable changes in the values of the ecological indices for the sunlight, moisture, and soil nitrogen. The absence of floods and the changes in the average annual temperature resulted in a violation of the ecological limits of the floodplains. Because of the stagnation of the water, the herbaceous layer was weakly connected and developed in a mosaic manner with a low diversity of species. We recorded an increase in its coverage and diversity in the summer months. At several locations, changes in the herbal composition and the appearance of the neophyte *Aster novi-belgii* were noted. On the sites that had an active water regime, which was characterized by the typical character of floodplain biotopes, the shrub layer was absent. Locations with an absence of flooding and water inflowing showed a trend of increasing coverage of a shrub layer dominated by *Cornus sanquinea*. The coverage of the tree layer did not change significantly compared to previous years. *Populus alba* was the dominant tree in several locations, but vital willows were also present in locations where the water level fluctuated (JAREM, 2000).

In 2010, because of high rainfall totals, regeneration of the tree floor occurred, specifically of the assimilation organs. In some locations, forest management and the planting of Canadian poplar monocultures began. Therefore, this year showed a meaningful increase in the coverage of the shrub layer since the monocultures had not yet reached a height of 5 m. Fig. 3 shows us the percentage of coverage of the individual plant floors, from which, compared to the year 2000 (Fig. 2) the changes are evident.

In several localities, the cutting down of willows and ash trees in a marginal part of the plots was recorded. Physiognomically, the composition of the shrub layer had not changed except for the abundant number of Canadian poplar samplings. In locations where flooding did not occur, there was a trend of strengthening the coverage of the plant layer, especially in shady locations where the herbaceous species had a lower amount of coverage. From the point of view of the composition of the species, changes were recorded only in the herbaceous layer (a decrease in the number of species), but the high

 Vol. 31, 2023, No. 1, 52 – 57

values of the similarity of the stand compared to the previous year showed stabilization of the layer. The lower coverage of the herbaceous layer and the reduction of a few nitrophilous species were caused by a spring flood. Nitrophilic species were again dominant, but some grasses were also present in the summer, although the dominant species was nettle (*Urtica dioica*) (JAREM, 2010).

At the Veľký Zemník 2/2 monitoring area, which is near Petržalka, we performed a detailed phytocenological recording of the herbaceous, shrub, and tree layers at the end of September 2020. By comparing this data with data from the phytocenological records from JAREM and the biomonitoring, we formulated a hypothesis based on which we found that changes in the structure of floodplain forests are influenced by changes in the ecological limits and the absence of floods. The changes in the dendrological composition and morphology of this floodplain forest precisely confirm this hypothesis. Urbanization and the construction of roads have disturbed the forest stands, which caused a change in the sunlight and microclimatic conditions of the forests.

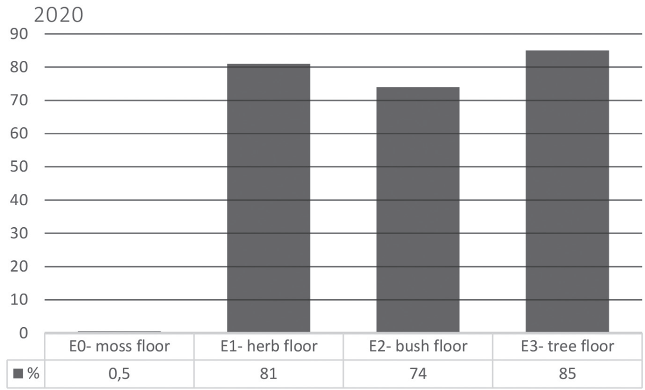

Fig. 4 *Average percentage value of the plant floor coverage in Petržalka for the year 2020*

These changes can be seen in Fig. 4. After evaluating the forms, we found that these changes caused the transformation of the floodplain habitats into a forest edge ecotone. After averaging the coverage of the monitoring areas located in the ur-

Tab. 1 *Phytocenological record from the Veľký Zemník 2/2 monitoring area (September 2020)*

Floor	Name Latin	English	invasive - non-invasive + invasive	Coverage (%)
tree	*Populus alba*	White poplar	-	15
	Fraxinus excelsior	Ash slender	-	6
	Acer campestre	Field maple	-	17
	Populus nigra	Black poplar	-	18
	Populus tremula	Aspen poplar	-	9
	Prunus avium	Bird cherry	-	0.5
	Acer platanoides	Norway maple	-	0.5
	Robidia pseudoacacia	Black locust	+	2
	Negundo aceroides	Ash maple	+	7
shrub	*Ligustrum vulgare*	Wild privet	-	-
	Crataegus monogyna	Common hawthorn	-	+
	Ulmus minor	Field elm	-	-
	Acer campestre	Field maple	-	+
	Sambucus nigra	Black elder	-	+
	Viburnum opulus	Guelder rose	-	–
	Populus alba	White poplar	-	1
	Negundo aceroides	Ash maple	+	-2/-4
	Rosa canina	Dog rose	-	+
	Fallopia japonica	Japanese knotweed	+	–
	Prunus spinosa	Blackthorn	-	–
herb	*Urtica dioica*	Stinging nettle	-	–
	Stellaria media	Chickweed	-	+[1]
	Parietaria officinalis	Upright pellitory	-	–
	Glechoma hederacea	Ground-ivy	-	-2/+2

Floor	Name Latin	English	invasive - non-invasive + invasive	Coverage (%)
herb	*Geum urbanum*	Wood avens	-	+
	Brachypodium sylvaticum	Lender false brome	-	–
	Impatiens glandulifera	Himalayan balsam	+	1
	Solidago canadensis	Canadian goldenrod	+	1/-2
	Populus alba	White poplar	-	3
	Fraxinus excelsior	Ash slender	-	+
	Acer campestre	Field maple	-	4/-4

ban environment of Petržalka, we can perceive a high percentage value of the shrub floor. Ideally, this value would be low, and shrubs would be found only on the edges of the floodplain habitats. Another fact that confirms our hypothesis about the changes in the ecological conditions is that *Acer campestre,* as well as other xerothermic species, is abundant in the given area on all the floors.

The absence of floods and the drying of floodplain forest soils could have caused these changes in the species' composition. Several JAREM annual reports mentioned that the presence of invasive species has been reduced in the reference sections that were flooded and that the regeneration of the habitat is occurring. Katz et al. (2005) investigated the delayed effects of flood control on a flood-dependent riparian forest in eastern Colorado, USA. They found that there was no significant difference between the regulated and unregulated sections of the South Fork River in the forest's structure. The reason for this fact is that there have been no major floods in any of the examined sections since the construction of the Bonny Dam. Scientists from the Slovak Academy of Sciences have studied long-term changes in the structure of softwood floodplain forests in our territory. They discovered these changes were mainly caused by the disturbance of the water regime. They concluded that, during the period monitored, there was a decline in autochthonous species and an increase in neophytes, which are slowly dominating domestic species (Mikulová et al., 2020).

In an annual agricultural report (Ministry of Agriculture and Rural Development of the Slovak Republic, 2010), the authors stated that the area of forest land in Slovakia has been increasing for a long time. In 2009, it reached 2,009,000 ha. Since 1950, it has increased by 238,000 ha (13.4%). The area of vegetation, i.e., the area of forest stands, has increased by 175,000 ha (9.9%) since 1950. Forest cover has been increasing for a long time as a percentage of the total area of forest land from the total area of Slovakia, which was approximately 41% in 2006. According to the results of the National Forest Inventory and Monitoring (NIML) of the Slovak Republic, which also included the so-called "white areas" (forests on non-forested land), Slovakia's forest cover is up to 44.3 ± 0.4%, which is positive, but they do not reflect the structural changes that have occurred during that period (Ministry of Agriculture and Rural Development of the Slovak Republic, 2010).

Mikulová et al. (2020) has stated that in the last 60 years, soft floodplain forests have been transformed considerably. The plant composition points to the indirect intervention of anthropogenic factors in the structure of the biotope. They concluded that the number and coverage of neophyte species have increased at the expense of native species. Their research shows that the territory of the Pannonian soft floodplain forests has changed from variable hygrophilic and mesophilic to homogenized mesophilic.

4 CONCLUSIONS

The survey points to the impact of climate change and anthropogenic influences on the biodiversity in a forested area in Bratislava, Slovakia. The current state and composition of the floodplains as shown in phytological records and field surveys, indicate an increase in the number of climate-sensitive species/habitats that have a narrow tolerance limit. Changes in the coverage of the plant floors show the sensitivity of floodplain habitats to changes in sunlight, climatic conditions, and the water regime.

By comparing the close-to-nature sections of alluvial forests with the urban environment of Petržalka, we can understand the stress that these biotopes are exposed to. The absence of floods in Petržalka have changed the ecological limits of soil moisture on which several taxa depend. There is also strong pressure on the forests due to urbanization as it has disrupted the compact area of the forest. Sunlight conditions have changed, and new transitional biotopes are formed. The violation of optimal and tolerance limits has led to changes in the environment, which is limiting for some species and restricts development, which is why the floodplains are regenerating into an ecotone on the edge of the forest. By changing the sunlighting conditions, the temperature in the growth increases, and evapotranspiration from the soil is higher, as a result of which these forests are drying out. The conditions created in this way are optimal for species that are not native to that environment.

The decline of autochthonous species in the structure of the forest communities in Petržalka can probably be attributed to anthropogenic interventions, improper management of these areas, and inappropriate regulation of watercourses, which have had a negative impact on the water regime. The alluvial ecosystems developed and were shaped according to human needs. The hydric function is quite variable because of the connection between the forests, water, and other components of the environment. Because of the individual factors that are necessary for the proper functioning of an ecosystem, the ecological conditions and structure of the forest play a central role.

By comparing the phytocenological records, the changes that affected the discussed area from 2000 to 2020 are clearly visible. According to Reháčková (2007), the original forest stands were preserved in locations that did not suit anthropogenic activities. From the map data, the fragmentation of the once continuous area of the floodplains is clearly perceptible. The field survey confirmed the hypothesis about the state and morphology of the floodplains near the built-up area of Petržalka.

Acknowledgments

This work was supported by the Slovak Scientific Grant Agency, Grant No. VEGA 1/0067/23, and the Slovak Research and Development Agency, Grant No. APVV-16-0253.

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