1 Sampling and characterization of the Warsaw Railway Station

The following paragraphs summarize the main findings and information regarding the sampling and characterization of the Śródmieście WKD Station Pavilion, one of the case studies chosen as part of INNOVACONCRETE project.

The information presented below is extended by five different annexes (Annexes 6.1, 6.2, 6.3, 6.4 and 6.5), where all the studies undertaken are described in full detail.

1.1 Information on the monument

General information

The Srodmiescie WKD Station Pavilion is a canopy structure part of the Warsaw Commuter Railway WKD Terminus. Located in Warsaw city centre, belongs to Poland's capital Cross-City railway Line and is under the Polish Railway Administration management.

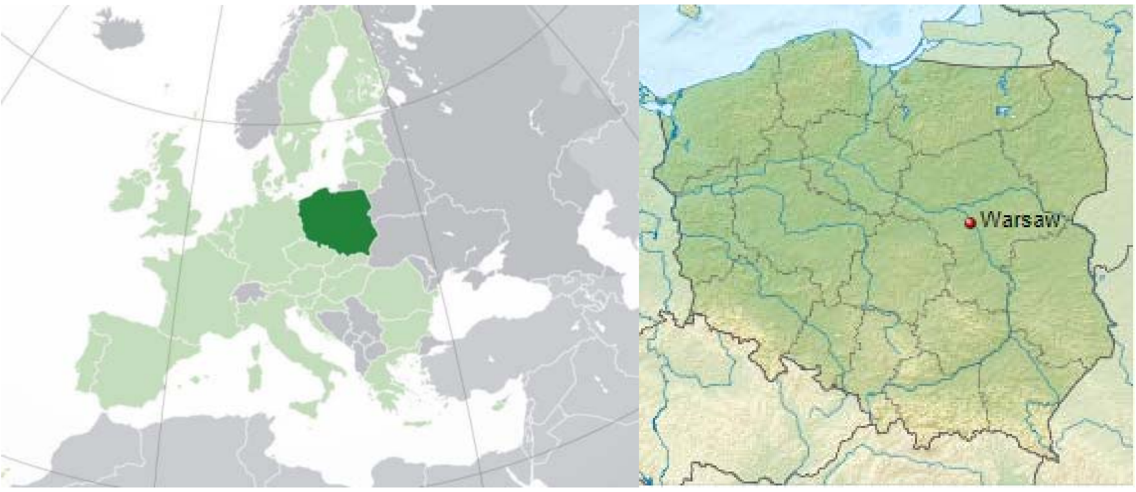

Figure 1: Maps showing the location of Lithuania and Kaunas within Europe and the country. Source: mapamundial.co, Wikipedia.

Figure 2: Map showing the location of Srodmiescie WKD Station within Warsaw. Source: Google Earth.

Designed by Arseniusz Romanowicz and Piotr Szymaniak in 1956, the structure was not built until 1963. Srodmiescie WKD Station, together with four other stations: Central Station, Ochota, Powiśle, and Stadium. creates a unique architectural development, that carefully renovated is still in use and perfectly serves its function.

Each of the station buildings was given a different form, which was a direct result of structural systems applied. Architects and engineers decided that they would search for a construction system, which would suit the station's functional needs, always based on reinforced concrete thin-shells of different, unique shapes.

Figure 3: Srodmiescie WKD Station East Pavilion elevation view. Source: Blazej Ciarkowski, Lodz University.

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Figure 4: The four other alternatives to Srodmiescie WKD Station. Source: AR/PS "The Architecture of Arseniusz Romanowicz and Piotr Szymaniak"ISBN 978-83-934574-5-8.

Each of the station buildings was given a different form, which was a direct result of structural systems applied. Architects and engineers decided that they would search for a construction system, which would suit the station's functional needs, always based on reinforced concrete thin-shells of different, unique shapes.

Besides Srodmiescie WKD Station not being the more important one of the five stations in terms of operation, it is the one that best matches the purposes of the project scope and its history is directly linked to the other four structures.

The station was designed for commuter and regional traffic, complementary to the Central Station, operating long-haul domestic and international connections. The station (platforms, ticket office etc.) is beneath the level of the street. The only part which is visible from the ground level is the reinforced concrete thin-shell canopy, which covers the stairs leading to the platform.

Originally, stairs on both ends of the platform were covered with reinforced concrete canopies, but only one of the two structures has survived to our times. The western structure was removed in the early 1990s to make room for the Swede Centre office building.

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Figure 5: Srodmiescie WKD Station perspective, showing both originally designed canopies. Source: AR/PS "The Architecture of Arseniusz Romanowicz and Piotr Szymaniak"ISBN 978-83-934574-5-8.

Structure description

Srodmiescie WKD Station Pavilion structural elements can be described as: foundation, vertical structure and horizontal structure. Further detail than the one provided next can be found in the Geometrical drawings prepared and attached as Annex 6.1.

Foundation

Unfortunately, all the original related documentation is missing. Thus, there is no possibility of knowing the type of foundation that the structure is using. Anyhow, it is worth highlighting that the Pavilion transmits its loads to the lower station walls and these ones do not show any sign of a bad mechanical or durable behaviour. Moreover, there is no sign in the structure of mechanical damages that could be related to settlements of the foundations.

Altogether, makes think that the foundation was properly designed and does not present any significant problem that can affect in the short term the structure stability.

Vertical structure

Originally, the structure was conceived with only four columns, built with reinforced concrete. Four steel additional columns were added to correct stability problems detected not very long after finishing the construction. Thus, altogether the structure has got 8 columns.

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Geometrically, the reinforced concrete columns are 3.10 m high and have got a section of 0.30 x 0.80 m^2. Steel columns are 2.73 m high and use a 0.10 x 0.10 m^2 section.

Figure 6: Srodmiescie WKD Station render, columns view. Source: INES Ingenieros 2018.

From the X-Scan test, it could be concluded that the concrete columns have three vertical bars and stirrups every 20 cm all along the column height. The reinforcement bars diameter could not be detected and there are no original drawings where to consult.

It is worth highlighting the fact of the columns having a coating all over them as well as a crushed stone layer that protects the concrete from the environmental exposure.

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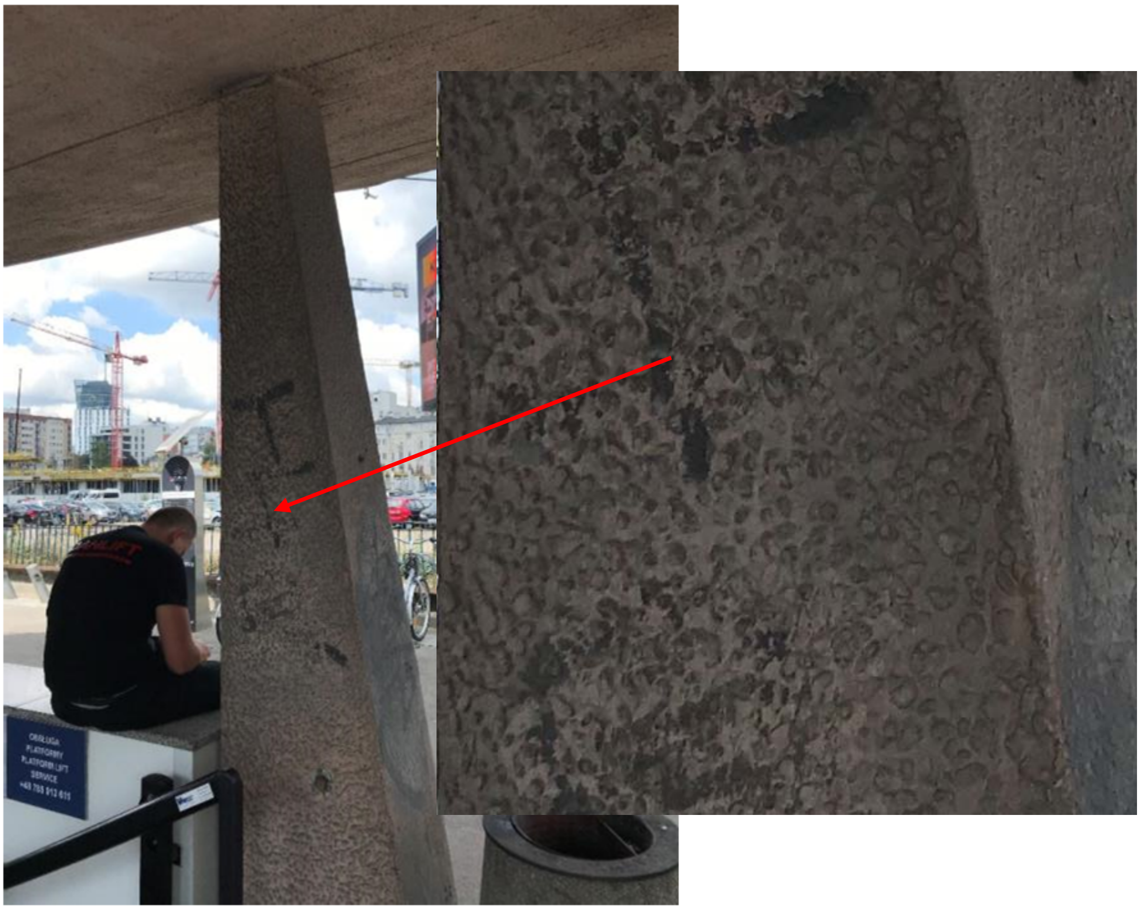

Figure 7: Srodmiescie WKD Station Pavilion columns detail. Source: INES Ingenieros 2018.

Horizontal structure

The main horizontal structural element is the pavilion deck, designed as a hyperbolic paraboloid thin-shell of variable thickness from 8 cm to 20 cm thick, built in reinforced concrete. This shell structure has got a waterproofing treatment on the top face based on a bituminous layer, which thickness goes from 4 mm on the edges to 10 mm in the centre. The bottom layer is left of concrete with any treatment.

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Figure 8: Srodmiescie WKD Station W-D5 test, with the measurement of the waterproofing layer thickness in the centre of the deck. Source: INES Ingenieros 2018.

Figure 9: Srodmiescie WKD Station Pavilion deck bottom face view, showing no surface treatment. Source: INES Ingenieros 2018.

Geometrically, the horizontal structure is symmetrical as it can seen in the following top view image:

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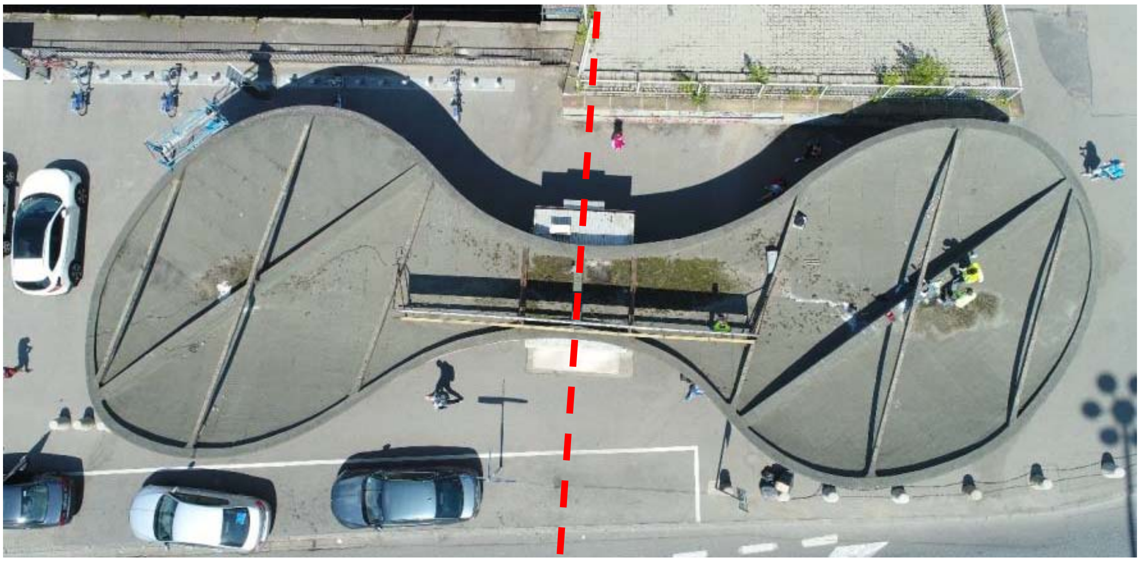

Figure 10: Srodmiescie WKD Station Pavilion deck drone top view, showing the deck symmetry. Source: INES Ingenieros 2018.

The deck has got a mesh reinforcement, with bars every 15 cm in both directions. The concrete covering for this element varies in the different measurements, reaching values of even 3 mm and never over 27 mm, which is under the 35 mm minimum concrete covering required by the Eurocode Standards for the environment the structure is subject to.

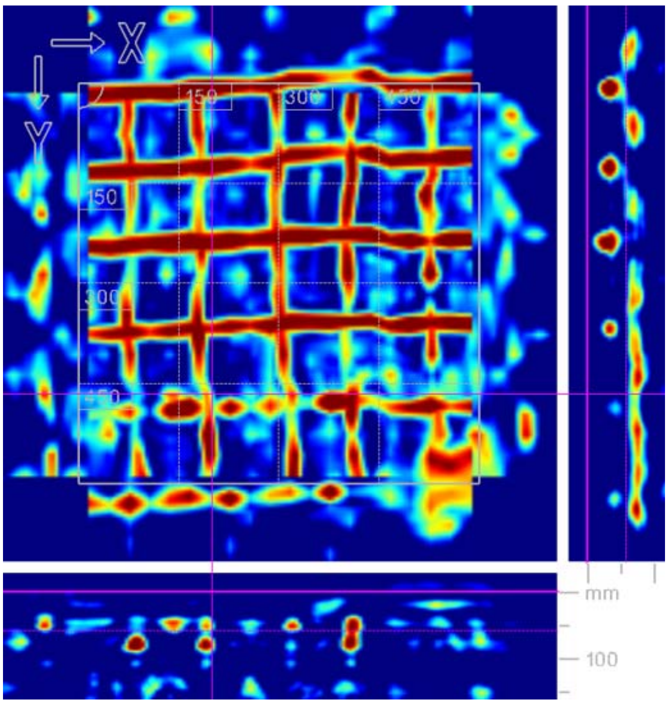

Figure 11: Srodmiescie WKD Station Pavilion deck X-Scan measurement, showing reinforcement mesh and concrete covering. Source: INES Ingenieros 2018.

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As part of the horizontal structure, there are two main beams that transfer the loads to the original four columns, plus one extra beam stiffening the centre section of the structure. The side beams are 0.35 m wide, with a variable thickness that ranges from 0.30 m to 0.75 m in the centre point, while the centre beam is 0.23 m wide and 0.40 m thick.

From the undertaken scanning, it could be concluded that the main side beams have got a vertical reinforcement composed by stirrups every 20 cm. In the horizontal sense, measured from the top section it can be seen that there are two bars, one at each extreme of the section. Finally, this horizontal reinforcement is placed every 20-25 cm in the vertical level. The measured concrete covering shows to be 5 mm in the most restrictive areas, not fulfilling minimum covering established by Eurocode.

The centre beam has the same reinforcement definition but limited by its geometry, showing equivalent concrete covering values.

It is worth highlighting that as the beams are covered with the waterproofing treatment, so the concrete covering underestimation is not as critical as it could be.

The following sketch shows the location of these main beams.

Figure 12: Srodmiescie WKD Station Pavilion deck top view sketch. Source: INES Ingenieros 2018.

The previous figure shows additional beams forming part of the deck. Besides the marked as main beams, the introduction of the four steel additional steel columns, required adding two new steel beams, aside the centre main beams.

These additional steel main beams are 0.15 m wide and 0.20 m thick.

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Figure 13: Srodmiescie WKD Station Pavilion deck side main beam view. Source: INES Ingenieros 2018.

Figure 14: Srodmiescie WKD Station Pavilion deck centre main beams view. Source: INES Ingenieros 2018.

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Besides the main beams, the horizontal structure is completed with two sets of three horizontal bracing beams. These beams have no waterproofing treatment as the others and the concrete is directly exposed to the environment.

These secondary beams have got a 0.12 x 0.17 m^2 section. From the undertaken scanning, it could be concluded that the bracing beam has got a middle bar and two very fine meshes in the top and bottom sections. The concrete covering of these elements is in all measurements under the limit established by Eurocode, being particularly sensitive to carbonation problems due to not having any protection as the other elements.

Figure 15: Srodmiescie WKD Station Pavilion bracing beams view, showing no protection. Source: INES Ingenieros 2018.

Construction period

As mentioned above the Srodmiescie WKD Station Pavilion was built in 1963 as part of the reconstruction of Warsaw Cross-City Line. It is important to contextualize the construction period, the location and the type of structure to understand why is considered an element of interest and considered worth studying it as part of this research project.

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Besides having being built in 1963, the station pavilion was designed in 1956, which in terms of concrete construction the world had already advanced knowledge and techniques for its implementation, after half a century improving the auxiliary means and concrete composition as well as the reinforced concrete behaviour theory.

Regarding the location, Warsaw was a city particularly affected by World War II, requiring an extensive reconstruction of buildings and infrastructure. In turn to the soviet restrained architecture, the proposed design supposed an emerging modernity within a communist society. On one hand reflects the technical inquisitiveness of the designers and their wish to adopt these new shapes, enabled by the use of reinforced concrete and already used in Western Europe; looking to set a landmark with the structure designed besides covering the functional needs. Secondly, they imply the start of a different way of thinking in the Eastern Europe, where people were anxious to shed light after the end of World War II.

In terms of structural typology, besides existing shell structures in Western Europe that were built 20 years earlier as it is the case of the Zarzuela Rasecourse, designed by Eduardo Torroja in 1934, which is another of the project case studies; due to the historical and communicational conditionings of the time, the designs of Arseniusz Romanowicz and Piotr Szymaniak, can be considered as experimental projects for their authors. In particular, the shape used for the Srodmiescie WKD Station Pavilion is a very rare geometry and unconventional within the engineering practice. There are writings of the architects, which reflect the problems they had during the construction of the structure, requiring changing things of the original design while the structure was being built and taking decisions not always technically supported.

The soviet architecture followed simple and repetitive shapes, which did not allow developing locally particular technically demanding construction skills among the contractors. Thus, it is worth highlighting that these new designs implied new construction techniques, which went from particular formworks, to the difficulty of placing the reinforcement and vibrating the concrete, what resulted in constructions that did not respond to an industrialized activity and can be considered more as prototypes.

No images from the construction of any of the stations could be found. Anyhow, the following figures show some examples of complex formworks.

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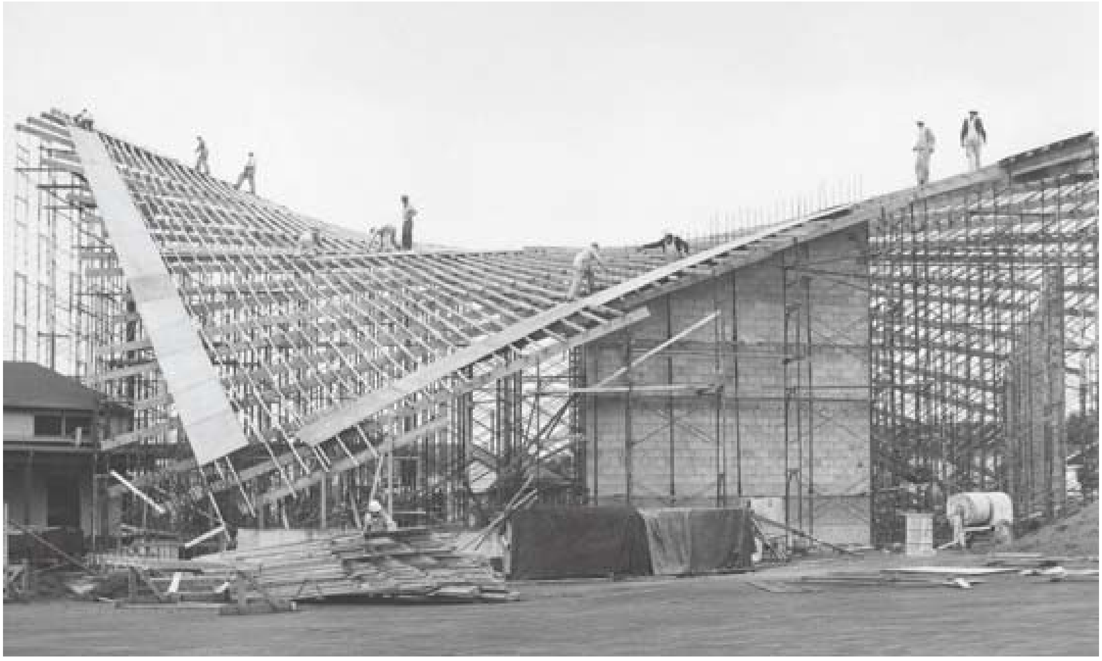

Figure 16: Spokane's St. Charles Church formwork for creating a shell structure. Source: www.inlander.com.

Figure 17: Concrete poring and vibration difficulties on a shell structure construction. Source: www.arch.mcgill.ca.

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Environment conditions

When undertaking a material characterization is important not only to focus in the material itself but in the environment in which it is located, analysing the boundary conditions to which the material is subject to. This is important as the material behaviour depends on the chemical composition together with its interaction with the environment in which is located. One same material will have different decay processes or these will develop in a different speed depending on the conditions that surround it.

Thus, conducting a Climate Study is important to understand the decay process that have been found active in the structure as well as for foreseen future problems that may arise. Regarding the project scope, the climate may also have an important impact on the performance of the products to be applied. Precisely, the case studies have been chosen, looking for different climate exposures in order to be able to analyse how the different products behave in different conditions of application.

For such purpose, the following environmental actions in Warsaw, where Srodmiescie WKD Station Pavilion is located, have been analysed:

Wind

The wind can produce concrete erosion, favour the removal of protecting coatings and accelerate certain decay processes. Warsaw´s average wind speed is 24 km/h. March and April register the highest wind speed, while July and August the lowest. As it can be seen in the following figure, the prevailing winds come from the West and the South-East direction.

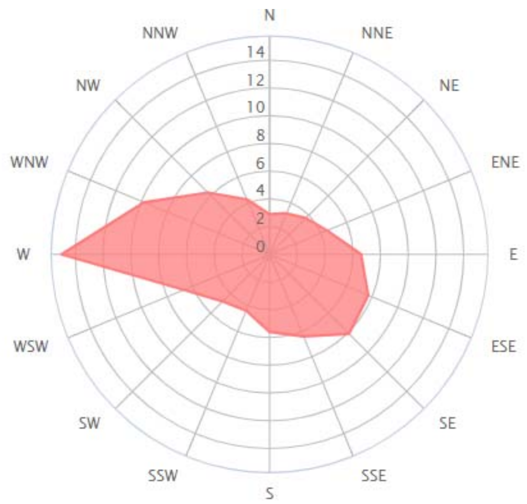

Figure 18: Warsaw Wind Direction distribution. Source: Windfinder.

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Both aspects have been consider while analysing the damages found in the structure and will be considered at the time of applying the products to be tested to make sure that different wind conditions are assessed.

Temperature

Concrete and in general, construction materials are particularly vulnerable to the thaw-ice cycle and not so much to extreme temperatures. These can affect during the construction process and the concrete curing but will not during the structure lifetime.

The repairing products to be applied may require particular ranges of temperature to ensure that the application and proper performance is granted.

Therefore, in regards to temperature, it is important to know on one hand the values for the different periods of the year and how does it vary in the winter in order to identify if the thaw-ice cycle can happen.

As the following table shows, maximum temperature register is from August and reaches the value of 37.1 ^{0}C, while the lowest value is from January, reaching -30.7 ^{0}C. In terms of thaw-ice cycles possibility, it is worth highlighting that according to the data shown, except for the months of June, July and August; the rest of the months, there are significant variations between the lowest and highest temperature register; always obtaining below zero values, what enables having thaw-ice cycles during most part of the year.

Table 1: Warsaw Temperature Data. Source: World Meteorological Organization

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high (°C)	13.8	17.2	22.9	30.5	32.8	35.1	36.0	37.1	34.5	25.9	18.9	15.4	37.1
Average high (°C)	0.6	1.9	6.6	13.6	19.5	21.9	24.4	23.9	18.4	12.7	5.9	1.6	12.6
Daily mean (°C)	−1.8	−0.6	2.8	8.7	14.2	17.0	19.2	18.3	13.5	8.5	3.3	-0.7	8.5
Average low (°C)	-4.2	-3.6	-0.6	3.9	8.9	11.8	13.9	13.1	9.1	4.8	0.6	-3.0	4.6
Record low (°C)	-30.7	-27.6	-22.6	-6.9	-3.1	1.8	4.6	3.0	-1.6	-9.6	-17.0	-24.8	-30.7

Precipitation

Water is the consequence of most of concrete problems, causing corrosion, carbonation, efflorescences, moiters, calcareous crusts, etc…

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Moreover, the existence of water on the concrete surface during the repairing products application might have some of influence on the performance as it will dilute the products and can also cause some chemical reactions not desired.

Warsaw, is Europe´s fourth driest capital, with yearly rainfall averaging 529 millimetres, the wettest month being July.

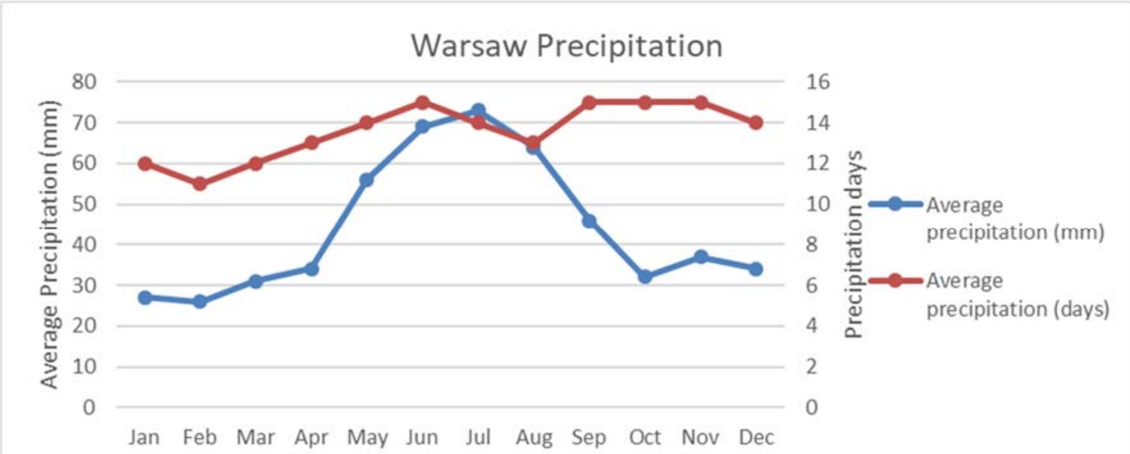

Figure 19: Warsaw Precipitation Data. Source: World Meteorological Organization.

Thus, the rain conditions are favourable, except for the fact that the rain high peaks are from June to August, which coincide with the mild temperature period. All this will need to be considered when deciding when to apply the products.

Snow

The snow can cause the same problems on concrete as the previously mentioned for the water. In the case of the products application it might interfere the same way.

In Warsaw city, winter can either be cold and snowy or windy and rainy. As the following figure shows, the average snow cover in winter is 5-7.5 cm.

This has been considered when analysing the decay processes discovered active in the structure and it will be taken in consideration for the repair products performance testing.

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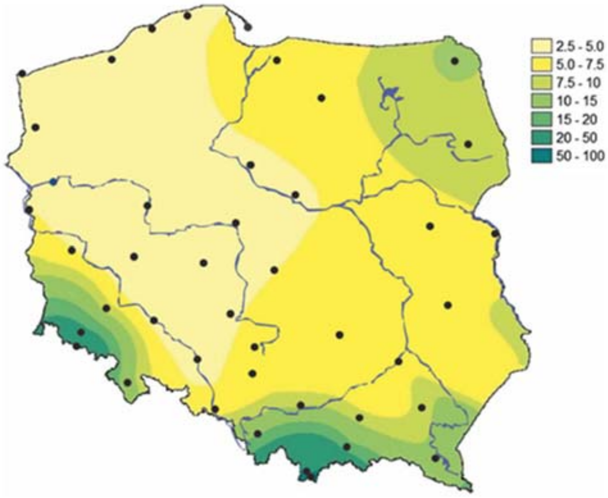

Figure 20: Mean Depth Snow cover (cm) in Winter (1952-2013). Source: Changes of snow cover in Poland by Małgorzata Szwed, Iwona Pinskwar, Zbigniew W. Kundzewicz, Dariusz Graczyk, Abdelkader Mezghani.

Solar incidence

The hours of sun has an influence on the water associated problems. Thus, a solar incidence study has been performed to determine if there is any significant difference between those areas which are more subject to sun incidence and those that are mostly in the shade.

Regarding the products application, this is another factor to have in consideration as the behaviour and performance of the repairing technique can be affected.

Besides the number of sun hours for the different year periods, the team has undertaken a particular study of solar incidence for the Srodmiescie WKD Station Pavilion. Such study enabled showing those elements of the structure which are more and less exposed to sun during the different moments of the year, taking in consideration the solar azimuth, zenith and path at the particular location.

Acid rain

Acid rain results when sulphur dioxide (SO2) and nitrogen oxides (NOx) are emitted into atmosphere and transported by wind and air currents. The SO2 and NOX react with water, oxygen and other chemicals to form sulfuric and nitric acids, which contribute to concrete decay and can react with the repair products being developed.

Poland is particularly vulnerable to acid rain and other forms of air pollution, especially from the emissions of coal-fired plants.

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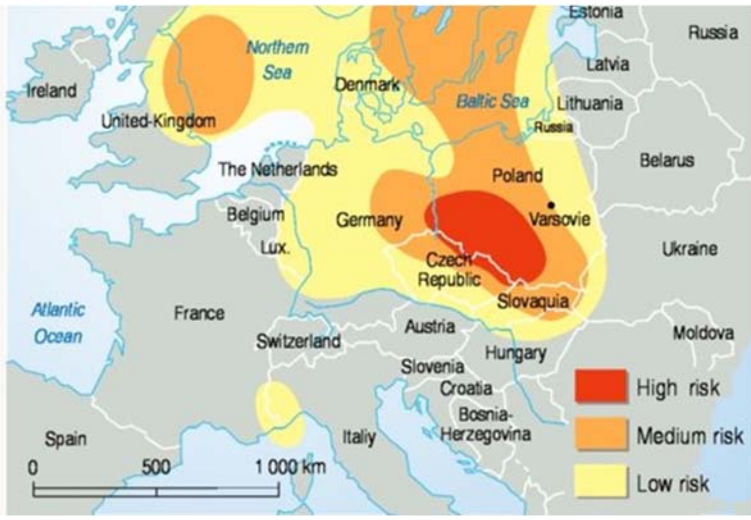

Figure 21: Acid Rain Risk in Europe. Source: World Meteorological Information.

As it can be seen in the previous figure, the city of Warsaw has medium risk of acid rain; therefore, it is an effect that needed to be considered in the characterization of WKD Srodmiescie structure.

All the previous information related to environmental conditions can be find furthered detailed in Annex 6.5 of this document. According to Eurocode Standards, this environmental conditions corresponds to a XC4 Environmental Exposure category, which will be used to check the material properties and have a reference of their behaviour.

Current condition

The main purpose of the sampling and characterization of this structure is using it for testing the performance of new developed repair projects. Thus, knowing the concrete conditions with which the structure was originally built is not of so much interest as knowing the current concrete properties as the products under development seek solving existing problems in concrete.

Therefore, knowing the current condition of the structure is essential to determine which products can be tested and which variables need to be monitored for studying their performance.

The first step for defining the structure condition was to conduct a damage survey and identify all the existing damages together with their location.

All found damages have been classified in three groups, depending on their origin: Durable, Mechanical or Anthropic. Now, the different damages are going to be listed. For further information about the amount of damages and exact location, please refer to Annex 6.2 of this document, where the damage mapping can be consulted.

Durable

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Within the damages with durable origin, the following ones have been found to be present in the structure:

- **Delamination:**

Figure 22: Delamination in Srodmiescie WKD Station Pavilion. Source: INES Ingenieros 2018.

- **Spalling concrete not showing reinforcing rods**

Figure 23: Spalling concrete not showing reinforcing rods in Srodmiescie WKD Station Pavilion. Source: INES Ingenieros 2018.

- **Spalling concrete showing reinforcing rods**

Figure 24: Spalling concrete showing reinforcing rods in Srodmiescie WKD Station Pavilion. Source: INES Ingenieros 2018.

- **Corrosion**

  Corrosion of steel reinforcement can be seen in the previous figure. Besides being present in the reinforcement, the top centre steel beams are also affected by this problem. Not the steel columns.

Figure 25: Corrosion in Srodmiescie WKD Station Pavilion centre beams. Source: INES Ingenieros 2018.

- **Moister**

Figure 26: Moisters in Srodmiescie WKD Station Pavilion deck bottom surface. Source: INES Ingenieros 2018.

- **Calcareous crusts**

Figure 27: Calcareous crusts in Srodmiescie WKD Station Pavilion edge beam. Source: INES Ingenieros 2018.

- **Peeling**

Figure 28: Peeling in Srodmiescie WKD Station Pavilion deck bottom surface. Source: INES Ingenieros 2018.

- **Deteriorated joint**

Figure 29: Deteriorated joint in Srodmiescie WKD Station Pavilion column bottom. Source: INES Ingenieros 2018.

Mechanical

- **Cracks**

Figure 30: Cracks in Srodmiescie WKD Station Pavilion bracing beams. Source: INES Ingenieros 2018.

Anthropic

- **Repairs**

Figure 31: Repairs in Srodmiescie WKD Station Pavilion deck bottom face. Source: INES Ingenieros 2018.

- **Black crust**

Figure 32: Black crust in Srodmiescie WKD Station Pavilion deck bottom face. Source: INES Ingenieros 2018.

- **Graffitis / Defacings**

  See Figure 7, showing graffitis on one of the structure columns. The structure has been recently painted, covering most of the existing graffitis.

- **Lichens and fungus high concentration area**

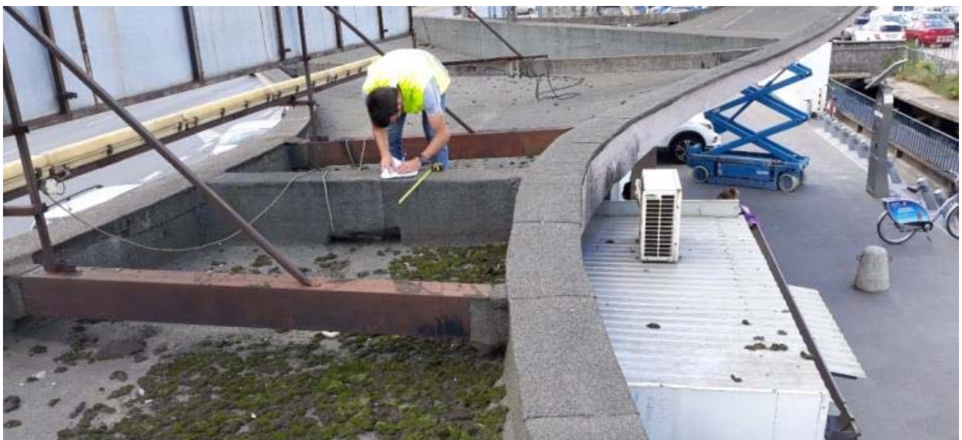

Figure 33: Lichens and fungus in Srodmiescie WKD Station Pavilion deck top face. Source: INES Ingenieros 2018.

Summarizing, the state of conservation is precarious. While the thin-shell, main beams and columns seem to be in relatively good condition besides some detected damages, the bracing beams have severe mechanical and durable damages that have made them loose a significant section as well as having serious corrosion problems that can lead to structural problems.

In regards with the products to be applied, the structure presents a significant variety of durable damages that want to be solved with the products that are being developed. Therefore, Srodmiescie WKD Station Pavilion is considered a good case study as it will allow testing the different products and seeing their performance in the particular environment previously described.

Previous repairing interventions

Having a record on past interventions is very useful as it allows having a better understanding of the problems that the structure is facing. It is like a clinic record, helps identifying the causes of the existing damages and the future behaviour of the structure.

In the case of Srodmiescie WKD Station Pavilion, PKP, the stakeholder, did not provide any register of previous repairs undertaken.

Anyhow, as it has been detailed in the condition section, the team could detect some past interventions just by a visual inspection. Moreover, by using the thermographic camera, some more could be detected. However, besides knowing that the structure has already suffered of repair interventions, the damage that was repaired is unknown together with what caused it; so the available information was not very of use.

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The only statement that can be made is that no major interventions could be detected, except for the known four columns and two centre beams that were implemented short after the construction but that were associated to excessive deflections and not to cracking problems.

1.2 Sampling activities

During the week of July 23rd 2018, as part of InnovaConcrete project, INES Ingenieros team conducted the sampling field campaign for the material characterization of the Srodmiescie WKD Station Pavilion. The team was supported by Błażej Ciarkowski and Adam Drozdowski, historians from Lodz University, who took care of arranging the permits dealing with PKP (structure stakeholder) for enabling the team work on the structure and obtaining the existing documentation of the same.

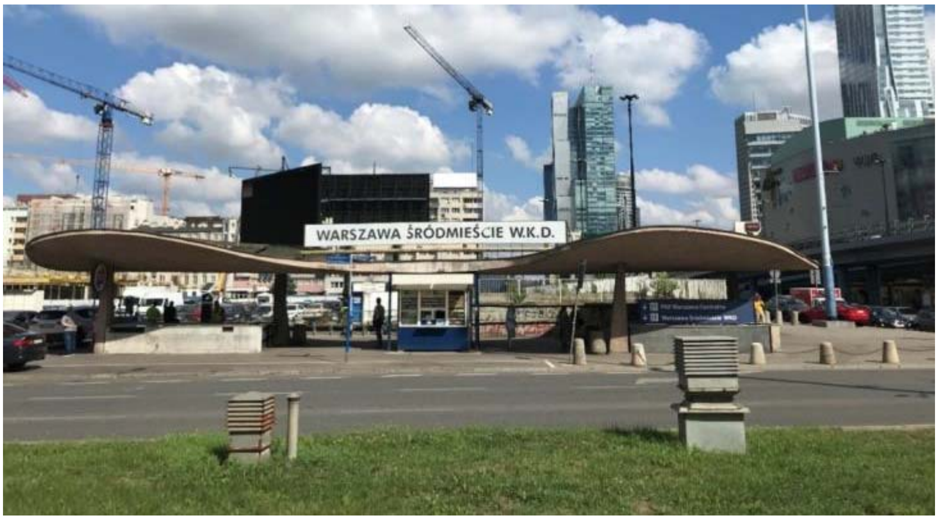

Figure 34: Srodmiescie WKD Station Pavilion elevation view. Source: INES Ingenieros 2018.

Figure 35: Srodmiescie WKD Station Pavilion aerial view. Source: INES Ingenieros 2018.

The main purpose of the material characterization is understanding the properties that define the concrete with which the structure was built as well as identifying the decay processes that are currently active or that can activate in the near future due to the material composition and environmental conditions to which is exposed to.

Geometrical definition

The first step for achieving this outcome has been to conduct a full 3D model that represents the structure geometry. Knowing the shape is essential to understand its structural behaviour, drainage system and the general structure exposition to the climate conditions. This 3D model was developed based in a drone survey that took images and laser scan information in order to build a point cloud file. Such model was checked on site to ensure the geometrical definition was properly built.

Figure 36: Srodmiescie WKD Station Pavilion render back view. Source: INES Ingenieros 2018.

Figure 37: Srodmiescie WKD Station Pavilion render top view. Source: INES Ingenieros 2018.

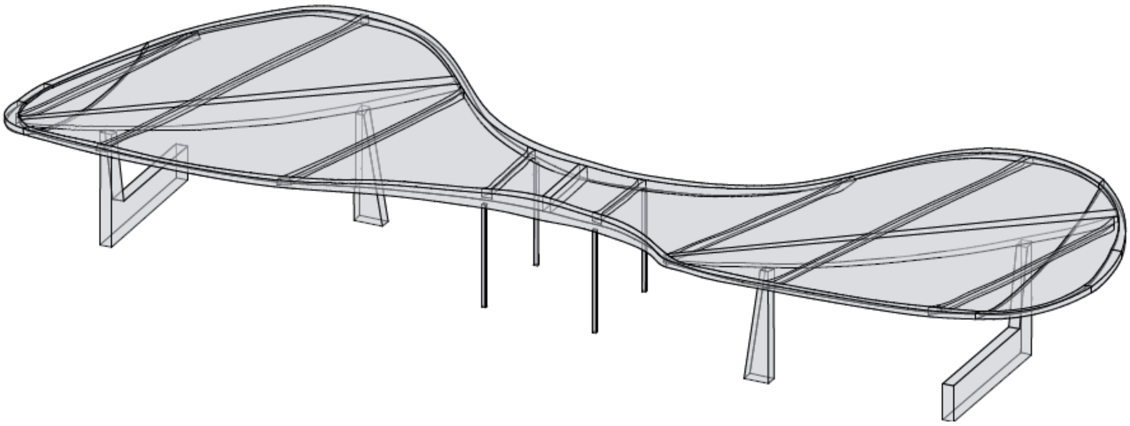

Figure 38: Srodmiescie WKD Station Pavilion render 3D view. Source: INES Ingenieros 2018.

Damage mapping

Using the geometrical definition, the second step was to develop a damage mapping of the structure. This will be essential for identifying possible spots where to apply the products in a future stage but it was also important to understand which are the problems that the structure is facing and design the sampling campaign not only to define the concrete properties but also to clarify doubts on the active decay processes.

Sampling

Once the damage mapping was completed, INES team conducted a set of destructive and non-destructive tests to finalize defining the material properties and condition. Annex 6.3 and 6.4 contain all the information regarding geometry definition, location and main conclusions from the non-destructive and the destructive samples taken. This section just presents a summary of the sampling undertaken and its purpose.

Destructive sampling

Regarding destructive samples, due to the impact they have in the structure, they were reduced as much as possible. Altogether, 7 different drills were undertaken from different structural elements of the Srodmiescie WKD Station Pavilion. Two different diameters were used; 4 samples with a

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diameter of 7 cm that were oriented to determine the concrete compressive strength, its density, abortion and porosity as well as the size and shape of the arid and the water-cement content and that required a minimum size to fulfil the laboratory tests standards; and 3 another drills 2.5 mm diameter, which were obtained for conducting a thin sheet test to obtain a microscopic view of the concrete composition.

Figure 39: Small drill extraction from Srodmiescie WKD Station Pavilion main beam. Source: INES Ingenieros 2018.

Both, big and small samples were used to study the depth of carbonation, which indicates the susceptibility of presenting corrosion problems among others. This was done by applying Phenolphthalein directly on the recently cut sample.

The location of the same was chosen following the next criteria:

- Have samples of concrete of as many different structural elements to see how the construction process and geometry could affect the concrete properties.
- Cover the different exposure conditions
- Obtain samples from different decayed concretes.

Besides these destructive samples obtained by drilling, the team could obtain extra samples of concrete from existing fallen pieces found in the top surface of the structure deck. These were used to analyse if the concrete contains any sulphates or chlorides by conducting salt extraction tests and using X-Ray diffraction and scanning electron microscope techniques.

Additionally, different paint, black crust from contamination and peeling samples were collected for their analysis in laboratory as well as samples of the existing coating painting covering the concrete of the columns.

Figure 40: Fallen concrete sample from Srodmiescie WKD Station Pavilion bracing beam. Source: INES Ingenieros 2018.

Figure 41: Pink and white paint samples from Srodmiescie WKD Station Pavilion columns and thin-shell. Source: INES Ingenieros 2018.

Figure 42: Black crust and peeling samples from Srodmiescie WKD Station Pavilion thin-shell. Source: INES Ingenieros 2018.

Non-destructive sampling

To support and extrapolate the results from the destructive tests, the following non-destructive tests were undertaken:

X-Scan and Pachometer measurements.

These were oriented to determine the concrete cover (thickness of concrete protecting the reinforcement or structural steel from corrosion) available in the different areas as well as for detecting those locations without reinforcement to enable the drilling to be conducted.

Figure 43: X-Scan measurements from Srodmiescie WKD Station Pavilion thin-shell bottom face. Source: INES Ingenieros 2018.

Figure 44: Pachometer measurements from Srodmiescie WKD Station Pavilion columns. Source: INES Ingenieros 2018.

The exact locations where these test was undertaken are detailed in Annex 6.3 but the criteria used was:

- Define the concrete covering of each structural element conforming the Station by taking several measurements that enable reaching to objective conclusions.
- Compare within each structural element between different areas, depending on its structural solicitation.
- Have an approximation of the reinforcement definition of the different structural elements.

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Schmidt hammer measurements.

Those locations where the drillings were done; were as well tested with the Schmidt hammer to calibrate it and be able to obtain measurements of compression strength and porosity from many other locations within the structures, without the need of damaging it.

Figure 45: Schmidt hammer measurements from Srodmiescie WKD Station Pavilion thin-shell bottom face. Source: INES Ingenieros 2018.

As explained in Annex 6.3, each measurement is composed of 10 readings to have a reliable result based on statistical analysis.

Moisture measurements.

The humidity differences between the different orientations within the different surfaces was studied to determine if there is any dominant pattern that can help identifying particular susceptible areas. A moister meter with 8 contact points was used for this purpose, applying it to the different structural elements, taking as well as in the case of the Schmidt hammer, 10 readings per measurement.

Figure 46: Moister measurement from Srodmiescie WKD Station Pavilion column interior face. Source: INES Ingenieros 2018.

Thermographic measurements.

Supporting the previous analysis, the team used a thermographic camera that highlights the temperature difference of the different areas. Images were taken at first time in the morning and after heavy rain to have on one hand those areas that more likely present moisture as well as to detect the water path when it rains. The complete structure was recorded with this device.

This techniqueenables having a broader view of the moister distribution along the structure and enabled detecting certain repairs and problems of the structure that were not visible for the

Figure 47: General thermographic measurement of Srodmiescie WKD Station Pavilion. Source: INES Ingenieros 2018.

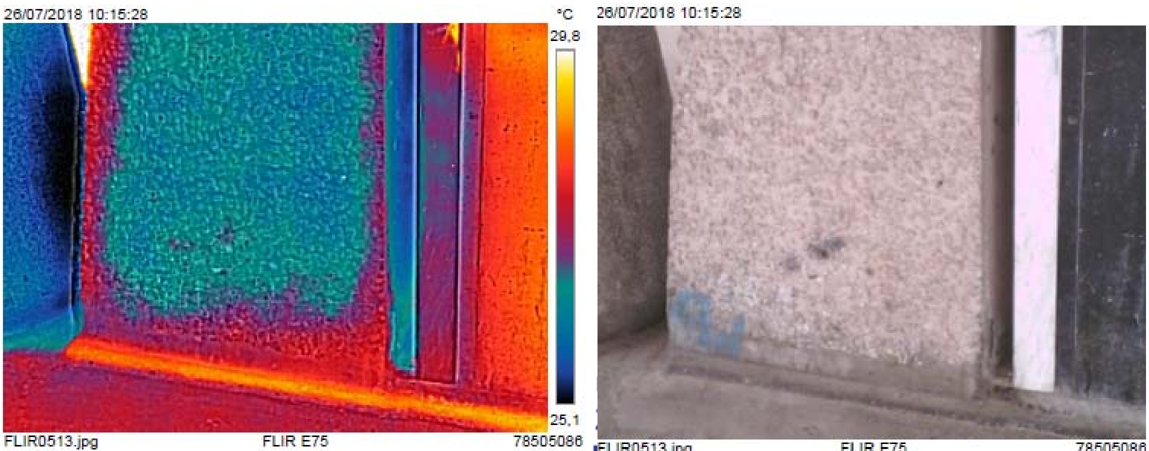

Figure 48: Thermographic measurement of Srodmiescie WKD Station Pavilion column bottom section showing moister problems not at sight. Source: INES Ingenieros 2018.

1.3 Results of the characterization

The characterization results are based in the samples taken and tests performed. The laboratory tests are directly linked to the type of sample. Previously the different samples obtained were described. Now the tests undertaken to each type of them are listed as introduction of the results presentation.

Drills (7 cm diameter)

- Accessible water porosity
- Density
- Size and shape of the aggregate
- Mechanical resistance
- Quantity of cement in concrete

Small drills (2.5 cm diameter)

- Thin sheet test
- Accessible water porosity
- Density
- Size and shape of the aggregate

Deteriorated samples

- Salt extraction (soluble salts)
- SEM
- X-ray Diffraction
- Sample weight

Inorganic samples

- FTIR

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Organic samples

- SEM
- X-ray Diffraction
- FTIR

The following paragraphs are going to expose the results obtained for the previous tests undertaken. For the project under development these values by themselves are the ones that are interesting; anyhow, its comparison with the Standard recommended values, provide useful information too. Therefore, besides presenting the values obtained, the recommended ranges for such values will be highlighted as well.

Moreover, the results of the destructive samples are completed with the non-destructive associated conclusions.

The mentioned results have been classified according to three groups, responding to:

- Intrinsic material properties
- Indicators of active or likely to be active decay process
- Location of the problems

What presented in this section is further developed in Annex 6.4.

1.3.1 Compositional and textural properties of concrete

The properties now detailed are those that define the intrinsic material properties.

Compressive strength and ultrasonic measurement

These two tests enable obtaining properties that reflect the quality of the concrete tested.

Three samples could be tested to compression, providing values with a difference of 10 MPa between each other, being the minimum value of 26.8 MPa. Moreover, the value obtained from the different Schmidt hammer readings is in all cases over 28 MPa, what allows concluding that 30 MPa is a reasonable value of compressive strength for the concrete used in the Srodmiescie WKD Station Pavilion in general terms.

Table 2: Compression strength and ultrasonic measurements, Warsaw samples. Source: INES Ingenieros 2018.

Code	Ultrasound measurement (m/s)	Concrete Condition	Compression Strength (MPa)
WD1	5107.6	Excellent	36.7

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WD3	9913.4	Excellent	26.8
WD7	5862,9	Excellent	33.3

Eurocode establishes that for an Exposure class XC4, the concrete should be minimum C40/50, which corresponds with a compressive strength of 40 MPa. This is two quality ranges over the structure compressive strength, not fulfilling the requirement.

Regarding the ultrasonic measurement, mention that according to the Leslie and Cheesman classification, the values obtained correspond to an excellent concrete.

The next sections, assess the different materials used for forming the concrete.

Cement content in concrete

The purpose of conducting a cement content test is determining a part of the composition of the used concrete to know if it fulfils the minimum requirements established by the international standards. This will be indicative of the potential decay processes that they can be subject to.

Eurocode indicates that structures under the Exposure class XC4, should have a minimum cement content of 300 Kg/ m^3 and the maximum should stay below 500 Kg/ m^3. The results obtained for the three tested samples are between 320 Kg/ $m^3$and 380 Kg/ m^3, so they are within the range. It is also worth highlighting the homogeneity between the values, showing that the proportions used for the different elements are very similar.

Table 3: Cement content in concrete, Warsaw samples. Source: INES Ingenieros 2018.

Code	**[Si] ppm**	**Çement content (%)**	**Cement content (kg/m^3 concrete)**
WD1	58.63	14.93	373.25
WD3	51.39	13.09	327.25
WD7	26.21	13.36	334
Average Value (%)	**45.41**	**13.77**	**344.25**

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Accessible to water porosity and density

This test allows determining the aggregate compactness, which is the relation between its real volume and its apparent volume. The greater the compactness, the smaller the volume of holes left by the aggregate and, therefore, the less amount of cement paste needed to fill them. Related with the project objective, the interest in knowing the porosity is crucial as all the products under development are thought to be applied by impregnation. Moreover, the porosity values are also linked to several decay processes.

In regards with the water porosity, the average obtained value is 7.2%. Standard values range between 7% and 24%, so the **concrete porosity is low**.

knowing the value of density, allows understanding if the obtained result corresponds to normal values or if for example, gives lower values that could come from the use of particular light aggregates, have a weird composition, etc…The tests undertaken provide a density mean value of 2.30 g/cm^3 , which is slightly low but nothing significant as the range provided by the Standards is from 2.40 g/cm^3 to 2.90 g/cm^3.

Table 4: Cement content in concrete, Warsaw samples. Source: INES Ingenieros 2018.

Code	Porosity accessible to water (%)	Density (g/cm^3)
WD1	7,40	2,29
WD3	7,22	2,33
WD7	6,96	2,29

Size and shape of the big and medium aggregate

This test is oriented to knowing the homogeneity and sizes of the arid used for developing the concrete. This, together with the values of dry density, saturated density and water absorption, has a direct impact in the compressive strength of the concrete.

According to the standards, the relation between the minimum and the maximum size needs to be over 1.4. From the three big samples tested, the laboratory results show that D (maximum arid size) = 46.7 mm, while d (minimum arid size) = 1.7 mm, what gives a D/d = 27.5. As this value is higher than 1.4, this requirement is also fulfilled. This requirement is also fulfilled individually in each of the tested samples.

From the smaller samples the values are very similar, always fulfilling the Eurocode relation between D/d. This allows concluding that the aggregate is quite homogeneous.

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Regarding the aggregates composition, the gravel is mainly composed of limestone, while fine aggregate is mainly quartz. Furthermore, other rock fragments of igneous or detrital origin were identified as part of both coarse and fine aggregate.

Coatings analysis

The columns and the deck have got a pink paint that was believed to be a coloured lime mortar directly applied.

After conducting a Scanning Electron Microscopy (SEM) analysis, the results were that there was a high concentration of calcium carbonate, bonds in water and presence of sulphates, which confirm the original theory.

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Table 5: Big Drills Images and aggregate size measurements, Warsaw samples. Source: INES Ingenieros 2018.

<table>
<tr><th>CODE</th><th>AGGREGATE MEASSUREMENTS</th><th>IMAGE</th></tr>
<tr><td>WD1-A</td><td>
<table>
<tr><th colspan="10">d/D= 2.5/12.1</th></tr>
<tr><td>1</td><td>12.1</td><td>10</td><td>7.4</td><td>19</td><td>5.3</td><td>28</td><td>4.5</td><td>37</td><td>3.1</td></tr>
<tr><td>2</td><td>11.6</td><td>11</td><td>7.0</td><td>20</td><td>4.9</td><td>29</td><td>4.3</td><td>38</td><td>2.8</td></tr>
<tr><td>3</td><td>10.6</td><td>12</td><td>7.0</td><td>21</td><td>4.9</td><td>30</td><td>3.9</td><td>39</td><td>2.6</td></tr>
<tr><td>4</td><td>9.6</td><td>13</td><td>6.9</td><td>22</td><td>4.9</td><td>31</td><td>3.8</td><td>40</td><td>2.5</td></tr>
<tr><td>5</td><td>9.5</td><td>14</td><td>6.3</td><td>23</td><td>4.8</td><td>32</td><td>3.7</td><td></td><td></td></tr>
<tr><td>6</td><td>9.1</td><td>15</td><td>6.0</td><td>24</td><td>4.8</td><td>33</td><td>3.6</td><td></td><td></td></tr>
<tr><td>7</td><td>8.1</td><td>16</td><td>6.0</td><td>25</td><td>4.8</td><td>34</td><td>3.4</td><td></td><td></td></tr>
<tr><td>8</td><td>8.0</td><td>17</td><td>5.7</td><td>26</td><td>4.7</td><td>35</td><td>3.4</td><td></td><td></td></tr>
<tr><td>9</td><td>7.6</td><td>18</td><td>5.7</td><td>27</td><td>4.6</td><td>36</td><td>3.2</td><td></td><td></td></tr>
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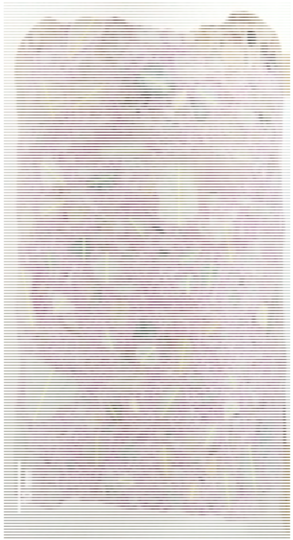
</td><td></td></tr>
<tr><td>WD1-B</td><td>
<table>
<tr><th colspan="10">d/D=1.7/13.8</th></tr>
<tr><td>1</td><td>13.8</td><td>10</td><td>7.1</td><td>19</td><td>6.1</td><td>28</td><td>4.7</td><td>37</td><td>3.2</td></tr>
<tr><td>2</td><td>11.5</td><td>11</td><td>7.1</td><td>20</td><td>5.9</td><td>29</td><td>4.5</td><td>38</td><td>3.1</td></tr>
<tr><td>3</td><td>10.6</td><td>12</td><td>7.0</td><td>21</td><td>5.9</td><td>30</td><td>4.2</td><td>39</td><td>2.9</td></tr>
<tr><td>4</td><td>10.3</td><td>13</td><td>6.5</td><td>22</td><td>5.7</td><td>31</td><td>4.2</td><td>40</td><td>2.7</td></tr>
<tr><td>5</td><td>8.6</td><td>14</td><td>6.5</td><td>23</td><td>5.5</td><td>32</td><td>3.6</td><td>41</td><td>2.5</td></tr>
<tr><td>6</td><td>8.3</td><td>15</td><td>6.5</td><td>24</td><td>5.3</td><td>33</td><td>3.5</td><td>42</td><td>2.2</td></tr>
<tr><td>7</td><td>8.2</td><td>16</td><td>6.5</td><td>25</td><td>5.1</td><td>34</td><td>3.3</td><td>43</td><td>2.1</td></tr>
<tr><td>8</td><td>8.1</td><td>17</td><td>6.4</td><td>26</td><td>5.0</td><td>35</td><td>3.2</td><td>44</td><td>2.0</td></tr>
<tr><td>9</td><td>7.4</td><td>18</td><td>6.1</td><td>27</td><td>4.8</td><td>36</td><td>3.2</td><td>45</td><td>1.7</td></tr>
</table>
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WD3-A

d/D= 2.7/18.6									
1	18.6	10	9.8	19	7.2	28	4.6	37	3.0
2	18.1	11	9.8	20	7.0	29	4.5	38	2.7
3	15.2	12	9.6	21	7.0	30	4.2		
4	12.4	13	9.6	22	6.8	31	4.1		
5	12.0	14	8.6	23	6.4	32	3.6		
6	11.8	15	8.5	24	6.3	33	3.4		
7	10.2	16	8.4	25	6.2	34	3.3		
8	10.2	17	7.7	26	5.5	35	3.2		
9	9.9	18	7.7	27	5.0	36	3.2		

WD3-B

d/D= 2.5/46.7							
1	46.7	10	6.3	19	5.0	28	4.0
2	18.8	11	6.0	20	4.8	29	3.5
3	8.6	12	5.8	21	4.8	30	3.4
4	8.1	13	5.8	22	4.7	31	2.5
5	8.0	14	5.7	23	4.7		
6	7.1	15	5.5	24	4.7		
7	7.1	16	5.4	25	4.5		
8	6.6	17	5.3	26	4.4		
9	6.6	18	5.1	27	4.2		

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WD7-A

d/D= 3.2/20.6					
1	20.6	10	6.8	19	3.2
2	16.5	11	6.2	20	3.1
3	13.0	12	5.4	21	2.7
4	12.3	13	5.2	22	3.2
5	10.5	14	5.1	23	
6	8.9	15	4.5	24	
7	8.1	16	4.4	25	
8	7.6	17	3.9	26	
9	7.4	18	3.3	27	

WD7-B

d/D=2.1/23.7							
1	23.7	10	6.7	19	4.8	28	3.2
2	21.2	11	6.4	20	4.6	29	3.2
3	10.9	12	5.9	21	4.2	30	2.7
4	10.6	13	5.8	22	4.2	31	2.6
5	10.6	14	5.4	23	3.9	32	2.6
6	7.8	15	5.3	24	3.8	33	2.6
7	7.6	16	5.1	25	3.7	34	2.4
8	7.2	17	5.0	26	3.4	35	2.1
9	6.9	18	4.8	27	3.3		

1.3.2 State of conservation of the monument

For defining the state of conservation of the monument, the team has focused in the following four aspects:

- **Concrete carbonation**, which reduces the concrete pH causing the corrosion of the steel in the case of entering in contact.
- **Material microstructure** looking for possible reactions taking place that can generate decay processes.

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- **Construction details** that can affect the concrete durability. Mainly focused on the concrete covering of the steel.
- **Environmental actions linked to geometry**: wind, sun, temperature, pollution but mainly rain and the moister patterns or drainage path linked to the damage mapping.

Now, the different aspects are exposed separately, highlighting their main results.

Concrete carbonation

Concrete carbonation has been analysed twice, once during the field campaign when undertaking the different destructive samples and secondly in laboratory when analysing them. Both cases were done by applying phenolphthalein to a recent cracked concrete and seeing the colouring it took.

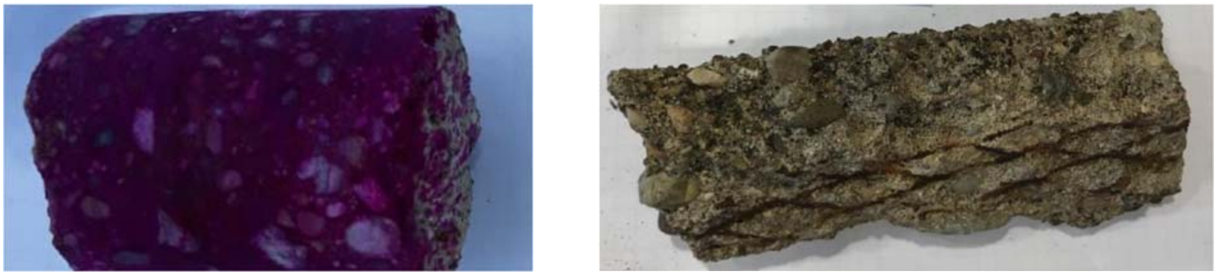

Figure 49: Phenolphthalein applied to different samples, showing no and complete carbonation respectively. Source: INES Ingenieros 2018.

Samples obtained from the main beams and the columns did not present any carbonation, but the deteriorated samples were completely carbonated. Thus, it can be concluded that the carbonation is consequence of the boundary conditions as the elements, which have no carbonation have got either a coating or a waterproofing treatment.

Mineralogical and microstructural characterization

Two main tests have been done in order to do the mineralogical and microstructural characterization of the deteriorated samples.

The first one consists on the X-ray Diffraction test (XRD) that allows the identification of unknown crystalline materials (e.g. minerals, inorganic compounds).

Secondly, Scanning Electron Microscopy-Energy Dispersive X-ray spectroscopy (SEM-EDX) test has been carried out, which allows obtaining microscopic images of all kind of materials, allowing to do microanalysis of the samples.

They both show that main mineral is calcite.

It is also interesting to highlight from the previous tests the lack of chlorides and sulphates found.

These tests have been at the same time supported by a saline extraction and by a FTIR analysis.

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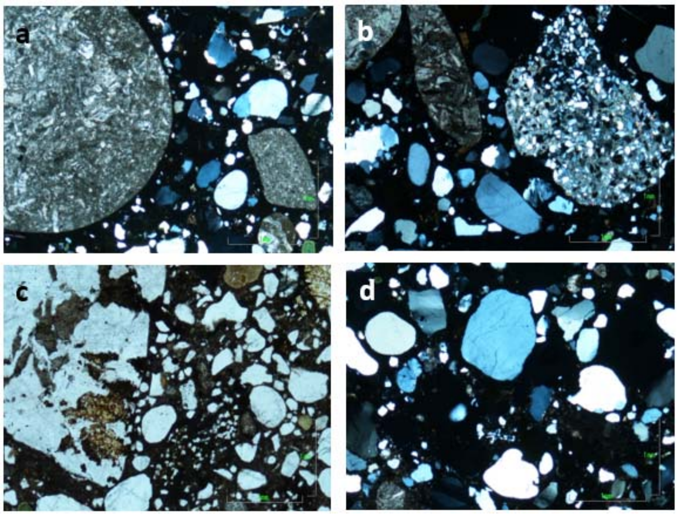

Figure 50: a) Gravel composed of carbonate rock fragment and sand of quartz; d) sandstone and carbonate rock as gravel constituents; c) fragment of and igneous rock (quartz, K feldspar and plagioclases) as a gravel particles and quartz, K feldspar and plagioclases as sand aggregates and d) sand mainly composed of quartz. a, b and d images taken with XPL and c with PPL. Source: INES Ingenieros 2018.

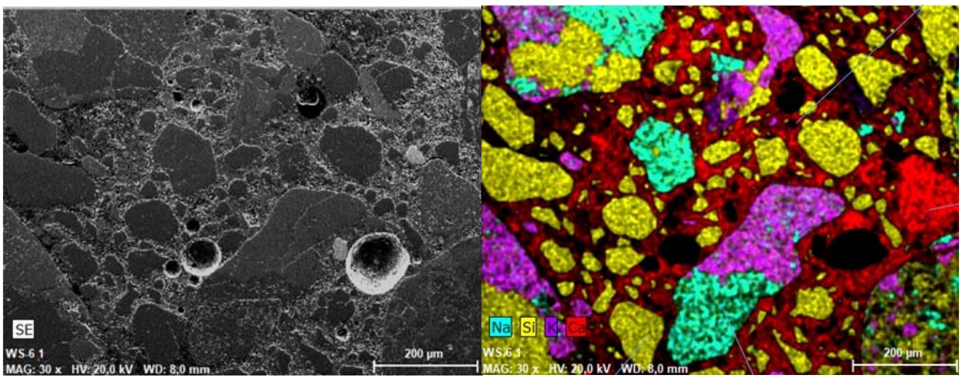

Figure 51: Left picture shows SEM image corresponding to WS6 sample and right image mapping showing the distribution of elements. Source: INES Ingenieros 2018.

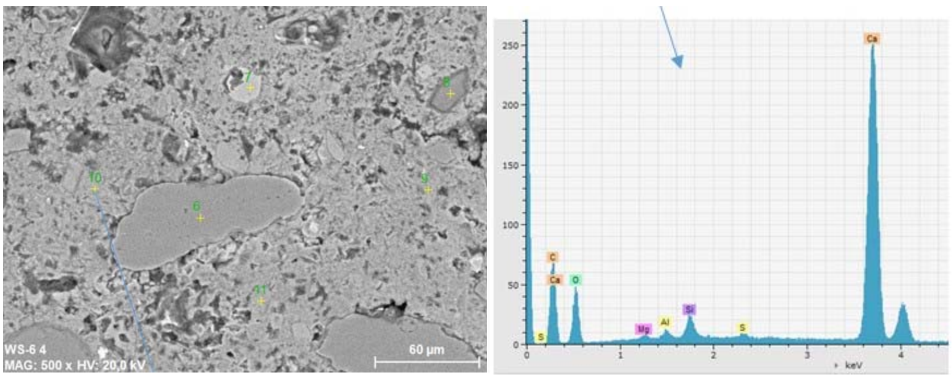

Figure 52: BSEM and EDX analysis corresponding to the binding phase (the light color plates are associated with aggregates). Source: INES Ingenieros 2018.

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The saline extraction had as main purpose to detect the existence of Chlorides and Sulphates within the concrete as they are the origin of several decay processes. According to Eurocode, the %Cl should be below 0.07, while the $\%SO_4^{2-}$ must be under 0.8. From the samples tested, the maximum values obtained are: 0.036%Cl and 0.096 $\%SO_4^{2-}$. **Both values are low and within the range of the Standards, so the concrete should not be affected by decay process related to chlorides and sulphates presence in the concrete matrix.**

Table 6: Saline extraction ICP and IC results, Warsaw samples. Source: INES Ingenieros 2018.

ICP	**Na**	**K**	**Ca**	**Mg**	**S**	**Si**	**Al**
	1.82	0.30	19.67	0.27	3.96	4.90	1.07
IC	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**Cl (%)[(1)]**	**NO_3^-(%)**	**SO_4^{2-} (%)**	
	3.7	-	10.2	0.036	-	0.096	

Finally, as an additional checking of the crystallization of the salts, these were analysed with Fourier Transform Infrared Spectroscopy, also known as FTIR Analysis or FTIR Spectroscopy. From this analysis, very similar results to what obtained by the saline extraction, showing again the high concentration of Ca and not providing any significant new data of interest.

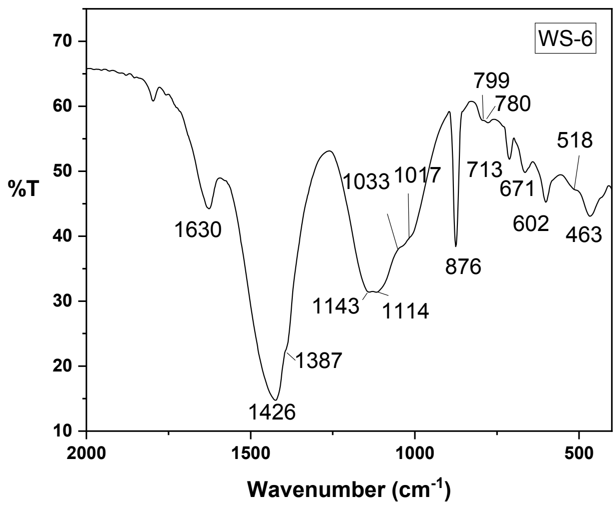

Figure 53: WS6 Sample FTIR analysis. Source: INES Ingenieros 2018.

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Construction details

One aspect linked to the construction process that is important for the proper performance of the concrete within time is the concrete cover. The monument is under Exposure class XC4, which according to Eurocode requires a minimum concrete covering of 35 mm.

From the 13 X-Scan measurements undertaken during the field survey, none had more than 20 mm of concrete covering. This is understandable for the thin-shell structure used as deck but the rest of the concrete elements have dimensions that would allow having the minimum concrete cover required by the Standards. Thus, it is a construction or project definition failure.

The conclusion is that the reinforcement bars are potentially vulnerable to present corrosion by carbonation and therefore, the concrete is also more likely to suffer from spalling problems.

Actually, this problem is already very advanced in the bracing beams, causing the loss of concrete section and the corrosion of the steel reinforcement.

Environmental actions linked to geometry

Besides the thaw-ice process, which as commented above is something that could be happening in the concrete but that it has been reduced due to the low porosity that the concrete has resulted to have; the rain is the main environmental action that can cause decay in the monument's concrete.

During the survey, the team had the good chance of having sunny and rainy days, so thermographic images could be obtained from the complete structure. By overlaying the results from this thermographic results and the damage mapping, the team could reach conclusions that can explain the origin of many of the problems that appear in the structure. Thus, moister, calcareous crusts, delamination, spalling problems and the presence of vegetation can be in most of the cases explained due to the locations belonging to a moister concentration area.

The thermographic analysis was completed with punctual moister measurements to confirm if those damaged areas actually had a higher moister percentage value than others and resulted to be true.

Thus, it can be concluded that the most of the durable damages are due to the rainwater exposure together with the concrete carbonation and low concrete cover values.

In the case of Warsaw, the existence of **acid rain** also has an influence that **speeds up the carbonation process** in the structure.

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Finally, there are other factors such as the air pollution that affect the structure, producing anthropic damages, which impact is mainly aesthetic but that can also end up in the future having chemical reactions.

1.3.3 Mapping of the damages

The damage mapping has been included as annex to this document, particularly Annex 6.2. Each damage has been collected in a sheet and commented with detailed pictures, which have also been added as part of the mentioned annex.

The different damages have been introduced in section 6.1.5 of this document.

Regarding the location of the damages it can be concluded that most of the durable damages coincide with those areas or elements that are more exposed to rainwater and that have no protection. Cracks and anthropic damages location do not respond to this pattern, and are located in areas of high stress or in a random way, respectively.

1.4 Summary

The conclusions reached are that the existing **concrete is of medium-high quality, with 30 MPa compression strength, low porosity and normal density**.

This, together with the high homogeneity in the aggregates and in the cement content, results in a **very stable chemical composition, where the only active decay process detected is the concrete carbonation**.

Regarding the boundary conditions to which the monument is subject to, highlight that the main external actions are the **thaw-ice cycles** due to variations of temperature during all year, except for the moths of June, July and August, where the temperature does not reach below zero in any moment. Luckily, the concrete has a low porosity, so the cracking problem linked to this effect is very unlikely and it actually does not show in the structure.

Moreover, the monument is subject to **precipitation**, that besides not being extremely high is quite constant along the whole year, what makes the structure be wet quite often. This rain, can have traces of acid rain, **being the main cause of the problems that the structure has currently got** as most of them are durable damages. The frequent precipitation, together with the poor drainage, missing protection of the bracing beams and low concrete cover values, makes the structure susceptible to present problems linked to moister. No particular damage or reaction obtained at laboratory could be linked to acid rain, thus, the influence of this one is considered low.

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Besides the durable damages coming from the rainwater, the monument presents other damages, which origin is anthropic or even some cracks that could be considered of a bad mechanical behavior. These last cracks in no moment can be considered a bad performance due to the concrete properties, but a non-proper reinforcement design. Most anthropic problems are repairs.

Altogether, the state of conservation is quite poor. The concrete is in good conditions and it only presents carbonation problems but the consequences of this decay process is already very significant in the bracing beams, implying a possible stability problem.

Focusing on the project future stages, regarding the mock-up samples development and the application of the developed products for the testing of their performance; the monument is considered a good example as it will be simple to reproduce the concrete properties and it will be **particularly good for testing the performance of the waterproofing and corrosion inhibition properties of the products being developed**. Moreover, as there are several cracks due to carbonation problems, **the consolidant product can be tested too**. A possible drawback for the products application can be the low porosity, as the new products being developed will be applied by impregnation.

Annexes

Further details about the results of the characterizations are available at the following link:

SRODMIESCIE_WKD_PAVILION_ANNEXES

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