



Dissertation

Master in Civil Engineering – Building Construction

**Assessment of structural changes in cement matrix
materials using virtual modeling, embedded and
acoustic sensors**

Trambitski Yahor

Leiria, November of 2020



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Dissertation developed under the supervision of Doctor Paulo Alexandre Lopes Fernandes, professor at Department of Civil Engineering of the Polytechnic Institute of Leiria and co-supervision of Doctor Dmitry Shabanov, professor at the Polotsk State University of Civil Engineering.

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RESUMO

O estudo da estrutura dos sistemas de cimento, a formação de defeitos iniciais no mesmo e a possibilidade de sua detecção em fases iniciais para evitar o desenvolvimento posterior tornou-se agora uma questão urgente. São igualmente relevantes os sistemas de monitorização do estado de tensão do betão e das estruturas de betão armado. A criação desses sistemas permitiria registar alterações estruturais numa estrutura concreta, para avaliar o grau desta alteração, evitando assim a eventual destruição do objeto em estudo.

O objetivo da tese é estudar a estrutura dos sistemas de cimento, nomeadamente a formação e desenvolvimento de defeitos iniciais na sua área, a possibilidade da sua detecção em fases iniciais. Criação de um sistema de monitorização do estado de tensão dos compósitos de cimento. Criação de uma ferramenta eficaz que permitirá uma monitorização contínua da integridade estrutural dos compósitos de cimento.

Os principais resultados do trabalho:

1. Desenvolveu um sistema experimental de monitorização do estado de tensão dos compostos de cimento, com base nos métodos de tensometria e de emissão acústica;
2. Concebeu e testou um modelo de sensor de manómetro interno (sensor profundo) para determinar as alterações estruturais dos compósitos de cimento;
3. Criei um modelo de pacote 3D do composto de cimento estudado para futuras investigações.

Palavras-chave: composto por cimento, estado de tensão de betão, manómetro interno, tensometria, emissão acústica, simulação virtual, monitorização

ABSTRACT

The study of the structure of cement systems, the formation of initial defects in it and the possibility of their detection at early stages to prevent further development has become an urgent issue now. Monitoring systems for the stress-strain state of concrete and reinforced concrete structures are also relevant. The creation of such systems would make it possible to register structural changes in a concrete structure, to assess the degree of this change, thereby preventing possible destruction of the object under study.

The purpose of the thesis is to study the structure of cement systems, namely the formation and development of initial defects in it, the possibility of their detection at early stages. Creation of a system for monitoring the stress-strain state of cement composites. Creation of an effective tool that will allow continuous monitoring of the structural integrity of cement composites.

The main results of the work:

1. Developed an experimental system for monitoring the stress-strain state of cement composites, based on the tensometry and acoustic emission methods;
2. Designed and tested a model of an internal strain gauge sensor (embedded sensor) for determining the structural changes of cement composites;
3. Created a 3D-package model of the studied cement composite for future research.

Key words: cement composite, stress-strain state of concrete, internal strain gauge, tensometry, acoustic emission, virtual simulation, monitoring

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1. INTRODUCTION

1.1 General

One of the most important tasks in construction is to ensure the safe operation of structures and facilities. Particular attention is paid to structures made of concrete, as the most common and demanded building material. Concrete, unlike other building materials, actively forms its properties during the operation of structures. Moreover, the ongoing changes have both a positive and a negative impact on the reliability of buildings and structures. Without understanding the physical processes that cause certain changes in concrete properties over time under the influence of force, as well as other factors, it is difficult to reasonably provide a given level of reliability of structures, create the most favorable conditions for their construction and operation [19].

The study of the structure of cement systems, the formation of initial defects in it and the possibility of their detection at early stages to prevent further development has become an urgent issue now. Monitoring systems for the stress-strain state of concrete and reinforced concrete structures are also relevant. The creation of such systems would make it possible to register structural changes in a concrete structure, to assess the degree of this change, thereby preventing possible destruction of the object under study.

1.2 Objectives

The purpose of the thesis is to study the structure of cement systems, namely the formation and development of initial defects in it, the possibility of their detection at early stages. Creation of a system for monitoring the stress-strain state of cement composites. Creation of an effective tool that will allow continuous monitoring of the structural integrity of cement composites.

To achieve the set goals, the following tasks were solved in the work:

1. A virtual dynamic model of the cement stone structure evolution in “Virtual Concrete and Cement Testing Laboratory” software has been built;
2. Created an experimental setup for monitoring the state of cement composites, including the methods of tensometry and acoustic emission;
3. An embedded sensor has been designed to monitor the stress-strain state of a cement sample from the inside;
4. Tests have been carried out to confirm the effectiveness of the created system.

1.3 Structure

Present research work consists of 4 chapters. Chapter 1 contains the introduction, objectives and structure of the work has been done.

Chapter 2 provides an overview of modern approaches to the study of the structure of cement composites, as well as methods for assessing its integrity, such as tensometry and acoustic emission. A hypothesis has been put forward about the possible application of a set of these methods in practice in order to obtain an effective device for monitoring the stress-strain state of cement composites.

Chapter 3 describes the materials used in the research, as well as the methodology for creating an embedded strain gauges and a monitoring system that makes it possible to assess the stress-strain samples of cement composites directly from the inside of the sample. A method for improving the sensor and monitoring system for further testing is also described.

Testing of the final system for monitoring the stress-strain state of a cement sample is presented in Chapter 4. The system combines active and passive research methods using tensometric and acoustic emission methods. Also, it was created a virtual model of the test sample composition structure, a dynamic cement stone structure formation model was built for the first 168 hours, and a 3D-package of the final structure was created too.

2. CONTEMPORARY CONCEPTS ABOUT THE CEMENT COMPOSITES STRUCTURE AND METHODS FOR ASSESSING ITS INTEGRITY

2.1 The concept of cement structure defects and methods of virtual modeling of cement composites

Studies carried out at the end of the last and beginning of this century, have established that a significant influence on the change in the strength and deformation properties of concrete is exerted by micro-destruction of its structure under the influence of force factors. It has been established that the process of micro-destruction begins at stresses in concrete much lower than its ultimate strength and can decay or develop in time [1]. However, the reasons causing the appearance and development of micro-destructions have not yet been fully investigated. Therefore, the study of the physical processes that cause the development of micro-destruction is of both scientific and practical interest.

As it's known, concrete failure mechanism associated with the formation and development of micro- and macrocracks under load action. The reason for the appearance of the first microcracks is the concentration of stresses near structural defects: pores, inclusions, dislocations.

According to modern concepts, microcracks appear at low stress levels – $\sigma_c=0,3f_{cm}$. The destruction of concrete begins with the development of cracks in the contact zone (matrix - filler) with their subsequent emergence to the surface. Contact cracks develop under the influence of shear stresses, cracks in the matrix – tensile stresses [5].

All these cases are caused by expansion (pressure) or contraction of the intraporous phase, leading to deformations of the structure, then to stresses, at a critical value of which cracks form in the structure [28].

From the standpoint of mechanics, the structure of a system is characterized by a set of properties that determine the ability of this system to resist destruction. It is advisable to differentiate this concept, which is complex in content, in relation to dispersed systems according to the following elements:

- 1) the substance structure in terms of chemical and mineralogical composition;

2) the structure of geometry, which does not depend on the structure of the substance and is determined by a group of parameters characterizing the geometric structure, the mutual arrangement in the volume of the elements (particles and pores) that form the final system;

3) the structure of the energy of communication between the individual elements of the system.

The combination of the listed elements form the concept of structure that determines the physical and mechanical properties of the material in question [29].

In the works of Kharitonov A.M. [37] was investigated the mechanism of concrete destruction based on level-by-level modeling of its structure. The author especially notes the significant influence of porosity on the mechanical properties of cement stone. To study the effect of pores on the stress-strain state of cement stone at the level of cement gel (matrix), he used the finite element method based on solid-state modeling, implemented in the ANSYS program, as a calculation method. The use of finite element method based on structural simulation models allows modeling the process of fracturing in a form that is close in physical essence to the real one, covering both the pore space and the solid phase. This technique takes into account the physical and geometric heterogeneity of the composite material [22,37]. An example of the structure destruction process imitation of fine-grained concrete is shown in Figure 2.1.

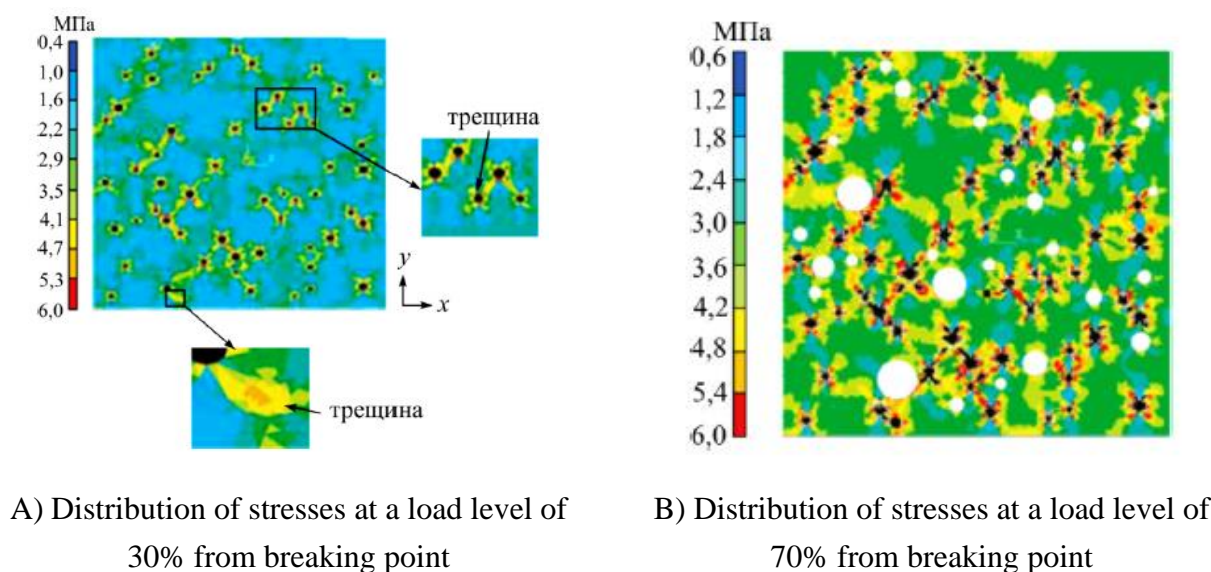


Figure 2.1. – Defects in the structure of fine-grained concrete at different load levels [9]

Kurbatov Yu. E. also considered the main problems arising in the solution of the problem of structural simulation of elements of cement concrete [22]. He proposed and generalized possible options for the implementation of structure modeling in specific software packages (SolidWorks, ANSYS, MSC.PATRAN-NASTRAN).

It can be concluded that the problem of structural simulation of cement composite elements is complex and requires careful study at each of the stages of modeling the matrix, filler and pores, thereby: – at the stage of creating their geometry and orientation of elements in space; – at the stage of assigning effective properties; – at the stage of fixing the created model and its loading.

2.2 Methods for determining the stress-strain state of cement composites

To correctly determine the residual life of structures, the initial data must be determined based on the results of field tests and measurements. Unfortunately, for most structures, obtaining reliable initial data is difficult, which certainly reduces the correctness of the calculations. The values of stresses arising in structures, as a rule, are taken according to the results of formalized calculations, which does not reflect the actual work of the structure [38]. It becomes necessary to look for reliable operational methods of obtaining initial data for calculations directly from full-scale structures. A way out of this situation is the use of telemetric systems for monitoring the state of objects.

2.2.1 Strain gauge method

Strain gauges are used as primary sensors to obtain information characterizing the parameters of the loading and stress state of the structure. The tensometric method, at the moment, is one of the most developed in the technique of measuring mechanical stresses. Converting information from sensors into a form convenient for further coding does not cause difficulties and can be implemented in any known way [16].

Experimental studies of concrete deformation under conditions of a complex stress state under short-term and long-term loading are associated with great methodological difficulties. The main problem of such studies is the limited or complete lack of access to the surface of the concrete sample, which makes it difficult to measure deformations with traditional measuring instruments. In addition, the measurement zone should be located as far as possible from the contact surface of the sample and the loading element because of the possible formation of cracks, which cause concentration of deformations at the place of the sensor sticker and fail from the break of the grating [23].

Even with a uniaxial uniform stress state, the stresses near surfaces parallel to the stress vector are somewhat different from the average stresses in the section. Consequently, surface deformations are only an indirect and incomplete characteristic of the average stresses in the sample. This circumstance also indicates the need to develop methods and tools for direct measurement of stresses. Direct measurement of stresses is an attempt to obtain information in the form of an electrical signal proportional to the stress, not strain [35]. Thus, strain gauges allow you to measure the real value of the relative deformation at the point of installation. Observations can be made continuously, including in automatic mode, and, thus, track the dynamics of changes in this value.

2.2.2 Acoustic emission method

During the operation of concrete structures, fatigue damage accumulates due to the effects of moisture and corrosive environments, various strengths and time durations of loads, leading to micro fractures in the material, temperature fluctuations, periodic freezing and thawing, as well as due to disruption of contacts between cement stone and aggregate. These damages at the initial stage of development are not detected by means of magnetic, eddy current and ultrasonic control, because such active methods do not carry information about the dynamics of the development of defects and the behavior of the object during the influence of the listed influences. The question of the safe operation of such objects can be solved only with the use of non-destructive testing (NDT) devices that are sensitive to insignificant developing defects. In this regard, the task of identifying growing cracks, including those at the initial stage of development, seems especially urgent. To solve such a problem, an integral survey method based on the phenomenon of acoustic emission (AE) has proven itself well [4].

Emission methods are based on the fact that at the initiation of microcracks or at the abrupt development of a main crack, the dynamically potential energy of a partially unloaded volume is released. This energy is spent not only on the formation of a new surface, but also on plastic deformation in front of the crack tip, on the vibrations of the newly formed surface, and also on other accompanying processes. Oscillations of the newly formed surface initiate an acoustic pulse lasting from tenths to tens of milliseconds. Each pulse, repeatedly reflecting from the sample surfaces and gradually scattering on material inhomogeneities, creates an acoustic signal, which is recorded in the form of stress waves on the surface of the product as acoustic emission (AE) [26].

The physical mechanism of acoustic emission is the motion of dislocations and their clusters in matter [32]. The generation and propagation of stress waves in concrete

structures has some specific features. By itself, concrete is a mixture of multicomponent polycrystals, which interact with each other according to physical and chemical laws, while its structure includes a system of pores and microcracks.

Therefore, acoustic emission signals, propagating to the surface of the sample, receive significant changes due to the dispersion of the speed of sound, transformation of wave types during diffraction, reflection, refraction, and attenuation (Figure 2.2).

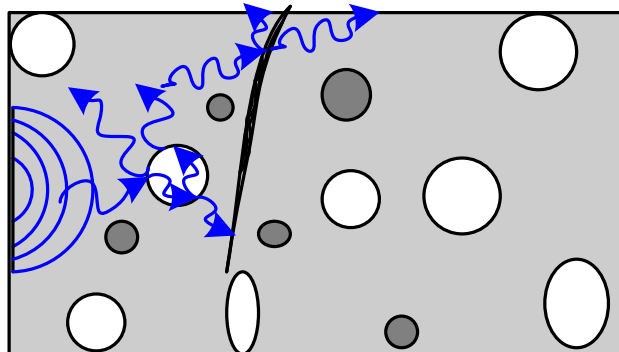


Figure 2.2. – Acoustic wave propagation inside a concrete specimen

Another peculiarity is that the laws of propagation of acoustic waves in concrete are very complex. This is due to the fact that concrete is an elastic-viscous-plastic inhomogeneous material, the physical and mechanical properties of which differ significantly from the conventionally accepted properties of a theoretical isotropic elastic medium. Concrete is distinguished by the inconstancy of the acoustic resistance of its components: cement stone, crushed stone or gravel, sand and pores filled with air and water [4]. Based on the above, we can conclude that in concrete with the growth of initial defects, complex processes of dispersion, diffraction, reflection and refraction arise during the propagation of acoustic waves.

Conclusion by chapter

1. When studying the stress-strain state of concrete, great importance should be given to its structure, its evolution, defects, their development and destruction.
2. Modeling the structure of cement composites is a complex process that requires the use of several software systems at once.
3. Combining several research methods (tensometric, acoustic emission and virtual simulation) will create an effective tool for monitoring the state of building structures, while providing full information about the object in question.

3. CHARACTERISTICS OF THE USED MATERIALS AND METHODS OF RESEARCH

3.1 Characteristics of the investigated materials

When creating a monitoring system, an important condition is to ensure the stability of the results obtained. For testing, it was decided to use standard mortar mixtures (cement M500 + water) [10,11]. As mentioned in Chapter 1, this choice is based on the fact that the structural models of the cement stone resemble large-pore concrete. They contain cement grains with non-hydrated nuclei and membranes of neoplasms, growing together in contacts [39]. The composition and geometrical parameters of each sample studied in this work are specified directly in the sections with the experiments.

3.2 Characteristics of the used equipment and the creation of an experimental setup for determining the stress-strain state of cement composites

3.2.1 Design of an embedded sensor

For a more detailed study of the development of deformations in concrete samples, Krasnovsky R.O. it was suggested in [20] the use of so-called “embedded sensors”. The author noted that this modification of the strain gauge has a good convergence of experimental and theoretical data. In works [5-7, 23], the study and use of this type of sensors was continued. In our opinion, these works do not cover a number of important issues, therefore:

- substantiation of the technology for obtaining and selection of components of the composition of protective mastic and comparison of characteristics with concrete (or the environment in which the sensor will be immersed);
- calibration of embedded sensors, assembly of a strain gauge unit for taking output data;
- the use of embedded sensors in conjunction with other methods for determining the stress-strain state of concrete.

This technology assumes the following algorithm for sensors manufacturing:

- 1) A thin layer of mastic (2,5 mm) was laid) into a mold (100X10X5mm);
- 2) After drying, a strain gauge was glued to the mastic, on which a second layer was applied on top. Only the leads from the strain gages remained free;
- 3) Soldering the leads to the wires, insulating this area;
- 4) After heat treatment, the sensors are removed from the mold.

A computer model was created, which is a schematic diagram of an embedded sensor construction, is shown in Figure 3.1.

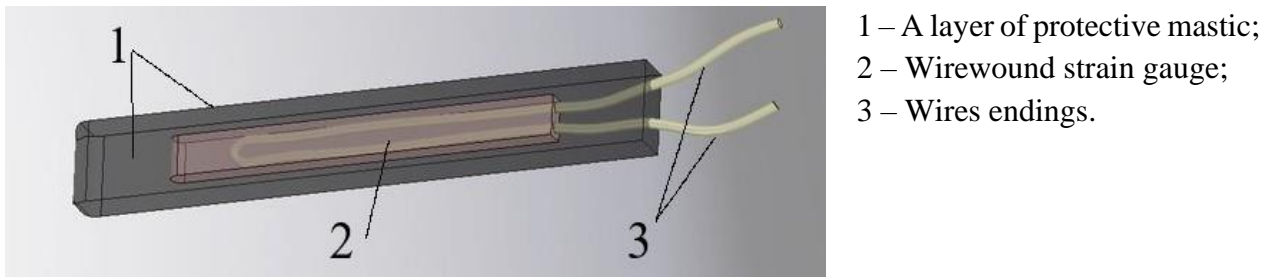
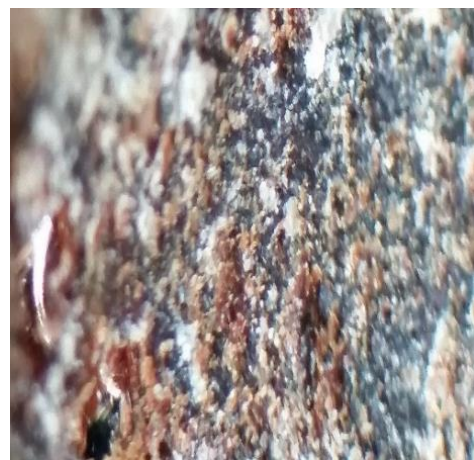


Figure 3.1. – An embedded sensor model

At the initial stages of this work, studies were also carried out on the behavior of glued strain gauges in cement stone without the use of the aforementioned protective mastic (protective corpus). The strain gauge was placed in a cement paste and kept there for 28 days, after which its performance was checked. A cement sample with a strain gauge inside was placed in a hand press under load. The strain gauge without protective corpus has stopped responding to ambient deformations. After the destruction of the cement specimen, the strain gauge under test was removed and placed under a microscope for further examination. Microscopic analysis was carried out using an Altami MET 5C optical microscope (Figure 3.2, a).



A) Optical microscope "Altami MET 5C"



B) Corrosion of the strain gauge wire after interaction with water

Figure 3.2. – Microscopic examination of wire defects in a strain gauge

In Figure 3.2 b, the development of corrosion on the working element of the strain gauge (wire) is clearly traced, which probably caused its failure.

As shown by the first tests of embedded sensors, made according to the technology presented in section 3.2.1, there are a number of problems associated with the introduction of the sensor into the concrete structure. The first prototype of that sensor was used for the tests presented in paragraph 3.2.3 and is shown in Figure 3.3.

The shape of the sensor has many right angles, which leads to an additional concentration of stresses in the internal structure of concrete, contributing to the premature rupture of bonds at the interface between the sensor and concrete, which leads to a decrease in the strength of the test sample as a whole.

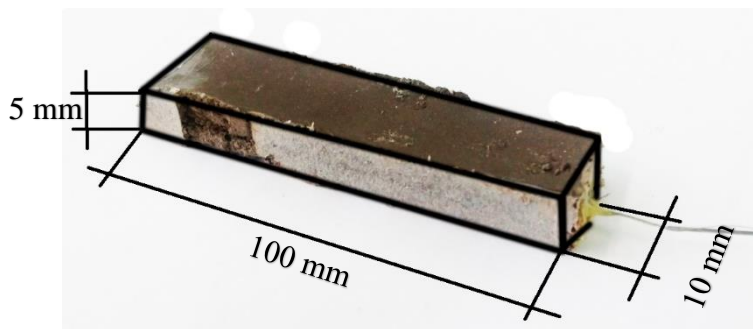
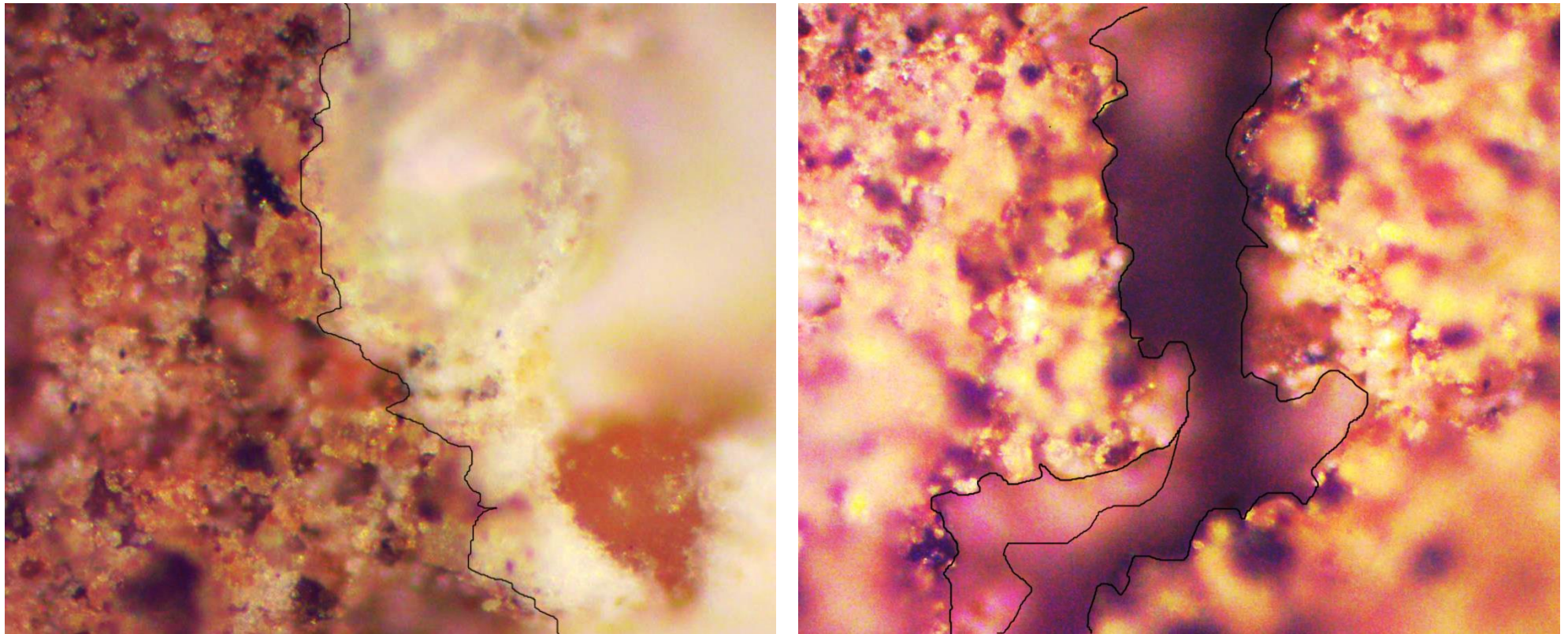


Figure 3.3. – First embedded sensor prototype

When creating a monitoring system, it is often impossible to install sensors in all structural elements of interest, because of it's necessary to use too many sensors and communication components, which inevitably leads to a significant increase in the cost of the final system. In this case, it seems rational to install sensors in the most loaded (according to the results of computer simulation) structural elements [34]. By linking the results of virtual and laboratory studies, we get a deeper analysis of the ongoing structural changes in the studied samples. Providing parallel use and processing of the data obtained by these two methods, the researcher can get the most rational and optimal result.

Figure 3.4 shows the microscopy of obtained concrete samples in paragraph 3.3. after destruction and removal of the embedded sensors from it.



A)

B)

A) Contact zone between embedded sensor surface and fine-grained concrete;

B) Defect (crack) on the embedded sensor surface after testing.

Figure 3.4. – Microscopy of the samples after testing

3.2.2 Designing a system for monitoring the stress-strain state of concrete samples using embedded sensors

The measurement of the indicators of the sensors was carried out using a strain gauge system made according to the "Winston's full bridge" scheme. When measuring with strain gauge equipment, it is important to provide a clear record of the process under study. Before the beginning and at the end of measurements, the calibration signal of each channel of the equipment should be recorded on the voltmeter. A schematic view of the assembled test setup is shown in Figure 3.5.

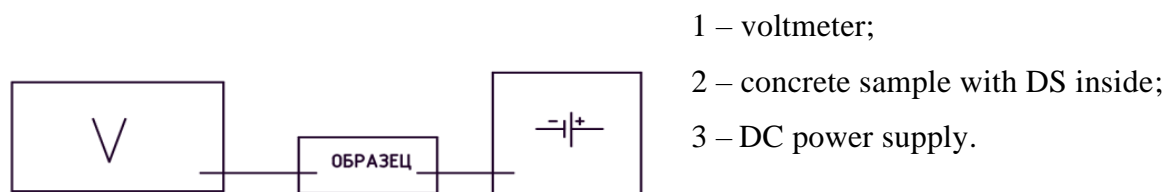


Figure 3.5. – Equipment used for sensors calibration

The load was fixed with a hydraulic press PGM-500MG4A. The press is equipped with an electric drive and a strain gauge force-measuring device. The peculiarity of the PGM-MG4 press is the absence of pulsations in the hydraulic system, microprocessor control of the loading process, which provides automatic maintenance of loading rates, fixing the breaking load, calculating strength taking into account the scale factor [31].



Figure 3.6. – Hydraulic press PGM-500MG4A

An experimental setup was assembled in the laboratory of Polotsk State University for further testing of concrete samples and determining their stress-strain state using strain gauges. A general view of this installation is shown in Figure 3.7:



- 1 – hydraulic press PGM-500MG4A;
- 2 – concrete sample with sensor inside;
- 3 – wires endings from embedded sensor;
- 4 – voltmeter;
- 5 – DC power supply.

Figure 3.7. – Equipment used for strain gauge measurements

3.2.3 Checking the performance of the monitoring system

To determine the stress-strain state of concrete, a concrete prism with dimensions of 100x100x200 mm was used as a prototype. The composition of the concrete mixture per 1m³: Portland cement (M500) - 1500 kg, sand - 500 kg, water - 300 liters. The applied embedded sensor is presented in section 3.1.

A small-diameter stretched wire was used to fix the sensors in a metal mold. Two sensors were placed mutually perpendicular to each other (along the directions of development of the main deformations) with a gap so that they did not touch. The layout of the embedded strain gauges in the prism sample is shown in Figure 3.8

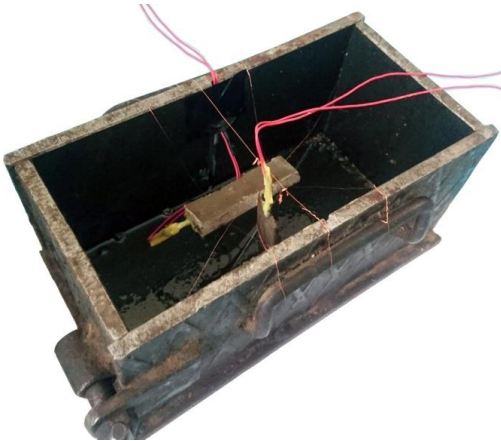
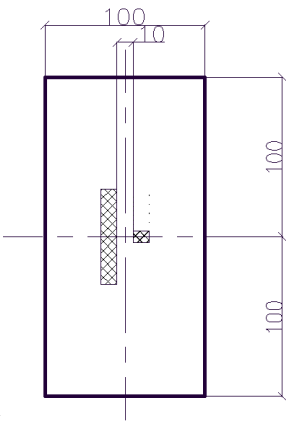


Figure 3.8. – Layout of embedded sensors in the formwork

The test results of the concrete prism were recorded both from the surface (using a strain gauge force meter of the PGM-500MG4A hydraulic press) and from the inside (using a voltmeter and embedded sensors). The obtained data are presented in Table 3.1.

Table 3.1. – Compression test results of concrete prism

No. of loading	Load, kN	Deformations, mm	Voltage, mV
1	0,92	0,601	1,27
2	8,48	1,204	1,4
3	96	1,506	1,471
4	197,64	2,018	1,483
5	247,87	2,475	1,573

According to the table, a graph (Figure 3.9) of the stress-strain state of a concrete prism was built with the overlay of readings obtained from the equipment presented in paragraph 3.2.2 (Figure 3.7) and embedded sensors presented in section 3.2.1

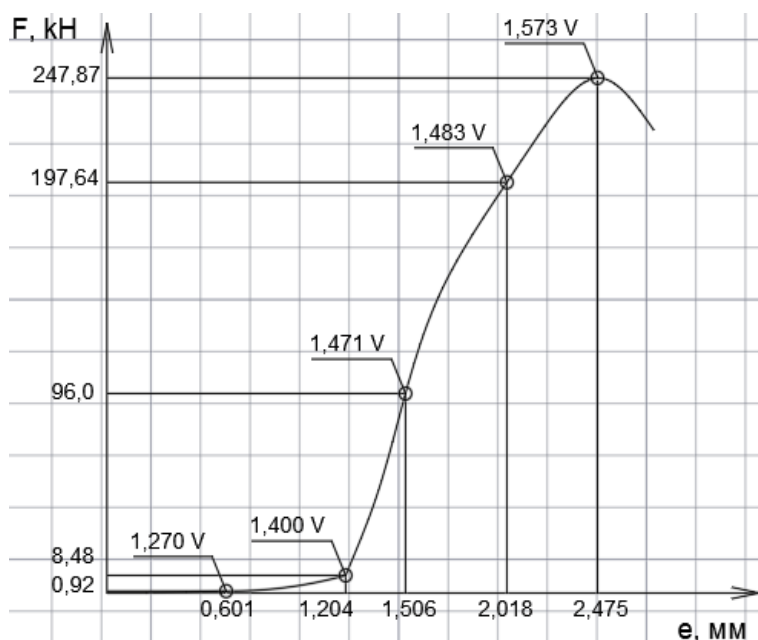


Figure 3.9. – Dependence of loading and deformations of a sample with the imposition of changes in the tensometric system electric voltage



Figure 3.10. – Specimen testing with embedded sensors inside

A change in the voltmeter readings shows that the embedded sensor was in operation and perceived internal deformations of the concrete. This graph has a direct proportional relationship between the growing deformations and the readings of the voltmeter connected to the terminals and registering the input signal from the sensor. This indicates that the chosen method is workable and requires further improvement.

It should be noted that the difference between zero and destructive load index is 0.303 mV. It can be assumed that for concrete of similar composition with the same compressive strength, when the load is removed before the voltmeter readings change by 0.303 mV, it is possible to avoid sample destruction.

Testing other samples with the use of embedded sensors will contribute to the emergence of a base of output values, which will be used to assess the stress-strain state of concrete of a certain composition and characteristics at time.

In the course of the experiment, it was found that internal sensors are able to perceive deformations of the medium in which they are placed. Further research and improvement of methods for fixing and recording readings from that sensors is required to determine the stress-strain state of concrete samples.

3.3 Improving of the monitoring system

3.3.1 Improving the design of the embedded sensor

The distortion of the measured stresses can be very significant and depends on the degree of mismatch between the deformative properties of the medium and the stress sensor, as well as a number of other factors. Therefore, the success of using stress sensors primarily depends on the solution of the issues of reducing voltage distortion in the zone of their inclusion in the medium. Fomitsa L.N. introduce additional requirements are introduced for sensors to improve the measurement accuracy [35]:

1. The deformation modulus of the sensor in the direction of the measured stresses must be higher than the deformation modulus of the medium;
2. The shape of the sensor should allow for minimal distortion;
3. The sensor must be selective, i.e. be sensitive only to the measured component of stresses and inert to the rest;
4. The readings of the sensor should not depend on the nature of the stress distribution over its working surface, i.e. have integrating properties;
5. Contact conditions with the medium must ensure reliable transmission of the measured voltages.

In the future, it was decided to use a cylindrical embedded sensor (Figure 3.11), which, according to the hypothesis, will allow avoiding the concentration of additional stresses at the interface of the media and meets all the requirements put forward earlier.

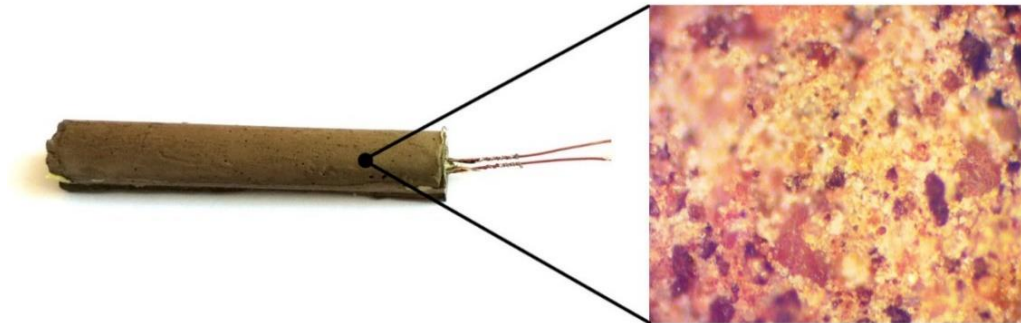


Figure 3.11. – Cylindrical shape embedded sensor

Having solved the main problems of the previously proposed method for the manufacture of embedded sensors and eliminating their geometric flaws, we can obtain an effective means of monitoring the internal stresses of cement composites.

3.3.2 Improvement of the monitoring system for determining the stress-strain state of concrete samples

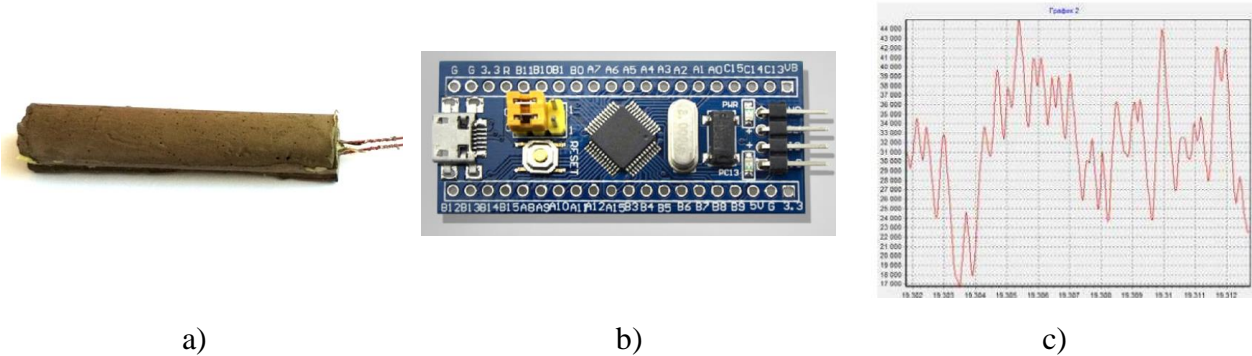
Functioning algorithm of monitoring system assumes the following operations:

1. Readout of readings from sensors, preparation of input parameters;
2. Coding of readings for each sensor, creation of a group signal;
3. Information transmission from each object to the base station;
4. Analysis of each state of the “N” objects and the residual resource [38].

For the implementation of such a system, only sensor is not enough, it should be a system that would allow collecting output information, as well as a software capable of processing it and transforming it into a readable format. In the work of S.A. Vabishchevich. and Zmitrovich S.Yu. [15] was presented a system for processing signals from sensor equipment. "PhyZModule" software has the following features:

- 1) selection of the analog-to-digital converter (ADC) of the device port from which the analog signal is received;
- 2) selection of the sensor and its calibration, which will allow converting the signal, through the formulas corresponding to it, into the desired measured value;
- 3) selection of a COM port through which data is exchanged between the PC and the device.

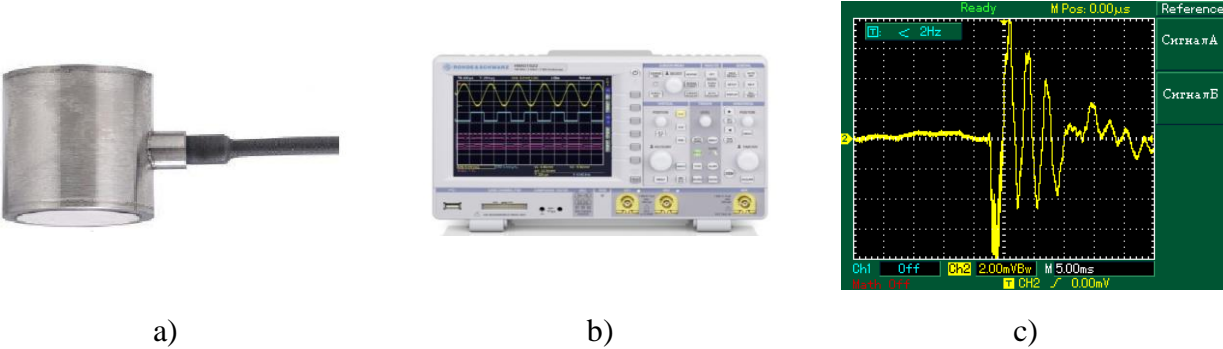
Working in group together we managed to adapt this program to the task at hand. The resulting device receives analog signals, with subsequent digitization and transmission through a communication channel to a computer. The main elements ensuring the operation of the created tensometry system are shown in Figure 3.12.



a) – embedded sensor; b) – microcontroller STM32; c) – PhyZModule software.

Figure 3.12. – Required components for the tensometry installation

In addition to the above research method, it was also decided to use in parallel the capabilities of acoustic emission control, which would allow for the necessary correlation and additional calibration of measurements made with the help of embedded strain gauges. The main elements ensuring the operation of the created acoustic emission system are presented in Figure 3.13.



a) – piezosensor; b) – oscilloscope; c) – image of the AE signal on the oscilloscope screen

Figure 3.13. – Required components for the acoustic emission installation

Due to the multimodality of propagation, transformation of waves of various types in a solid, attenuation of high-frequency components and resonance properties of the receiving equipment, the AE signals recorded at the sensor output have the form of a radio pulse with an exponentially decaying oscillation amplitude (Figure 2.13 c).

The AE source in the sample emits spherical longitudinal and transverse waves. In this case, the high-frequency component of the signal undergoes attenuation due to

the direct proportional dependence of the attenuation coefficient in the material and frequency. Considering the features of the propagation of the waves listed above, signals arise whose amplitude decreases with distance much more slowly than for a spherical wave. As a result, this type of signals is recorded predominantly.

The main task of AE control is to identify indicators that reflect the formation and growth of cracks in a concrete structure, such as the place and time of formation, assessment of the size of a crack, and its evolution. Therefore, it is important to select and process the listed information from the general data set. First of all, AE streaming characteristics are used, such as activity, total count, number of pulses, and total count rate. Table 3.2 connects the flow characteristics of the AE with the deformation mechanism during the entire test of the cement sample.

Table 3.2. – Classification of AE parameters depending on the integrity of the cement stone

Deformation and fracture characteristics	Characteristics of the AE phenomena:
compaction stage (0 ~ (0.3–0.5)) of breaking point: - shifts of the initial defects of the material; - breaking individual structural bonds;	single (rare) emission with weak amplitudes of high frequency signals
microcracks appearance stage (0.3 ~ 0.8) of breaking point: - occurrence of microcracks and microdefects in local zones of microdestruction; - a developing network of microcracks is formed;	high frequency of pulses and an increase in their amplitudes
macrocracks occurrence stage (> 0.8) of breaking point: - formation of main cracks emerging on the surface; - the rapid development of destruction;	strong emission with large amplitudes of low frequency
active destruction stage (> 0.96) of breaking point: - complete destruction of the material;	short-term existence of the emission with its rapid increase before the destruction of the sample

A schematic diagram representing the final version of the system for monitoring the stress-strain state of cement composites, combining the two previously mentioned research methods, is shown in Figure 3.14.

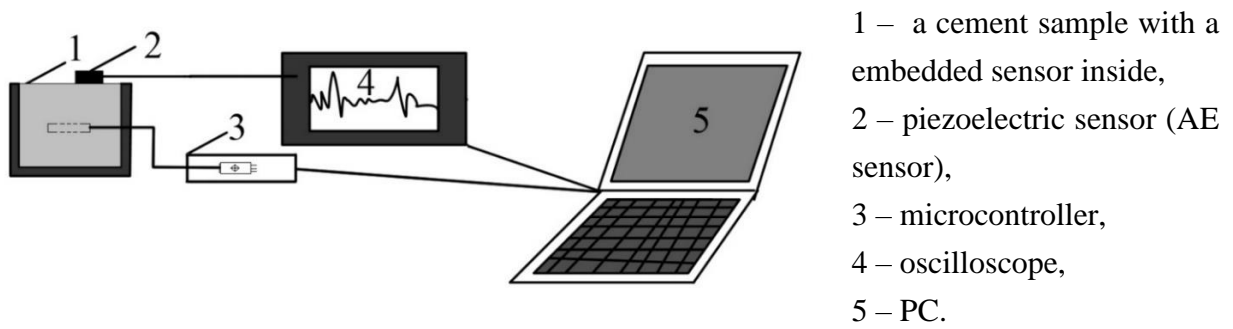


Figure 3.14. – Schematic diagram of the assembled monitoring system

In the future, this complex will be used to determine the transitional stage of cracking of concrete and reinforced concrete structures, proceeding from their energy levels, according to the parameters of the sound wave (which in turn characterizes the obstacles encountered) and a embedded sensor characterizing mechanical changes directly from the inside of the structure.

3.3.3 Checking the functionality of the new monitoring system

To determine the stress-strain state of the cement paste, 3 cement cubes with dimensions of 70x70x70 mm were used as prototypes. The water-cement ratio of the mixture is 0.4. Before testing, cubes were weighed to determine their average density. In this experiment, we used a cylindrical sensor presented in section 3.3.1.

In samples No. 1 and No. 2, cylindrical sensors were placed mutually perpendicular to each other (along the directions of development of the main deformations) with a gap so that they did not touch. Sample No. 3 was molded without embedded sensors inside.

The test results of cement cubes were recorded from the surface and from the inside using the system presented in paragraph 3.2.1. The test results for three samples are presented in table 3.3.

Table 3.3 – Characteristics of cement specimens

Sample No.	W/C	Cement, kg/m ³	Water, kg/m ³	Density, kg/m ³	Compressive strength, MPa
1	0,4	300	120	1,99	28,94
2	0,4	300	120	1,985	30,33
3	0,4	300	120	1,975	38,04

Parallel to each other, graphs of the stress-strain state of a cement sample from a hydraulic press and changes in the voltage of embedded sensors were carried out using the PhyZModule software. The data were recorded throughout the entire loading cycle and then synchronized in time.

Throughout the test, voltage changes were recorded by sensors located perpendicular to the applied load (horizontal sensor). Vertically positioned embedded sensors, no changes in the “voltage - time” graph was not given.

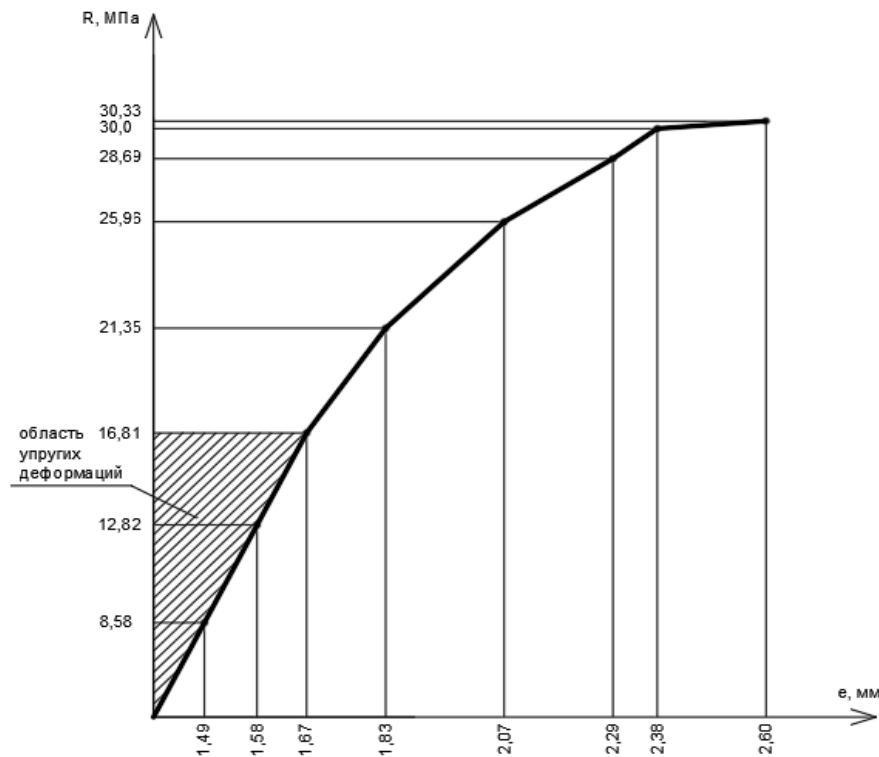
Analyzing the presented graphs and table 3.3., we can draw the following conclusions:

- When an embedded sensor is introduced into the structure of the cement system, we somewhat reduce the strength of the sample itself, while the density remains practically the same as in the sample without the sensor installed. Further testing is required to determine the effect of the embedded gauge on the structure of the cement stone;

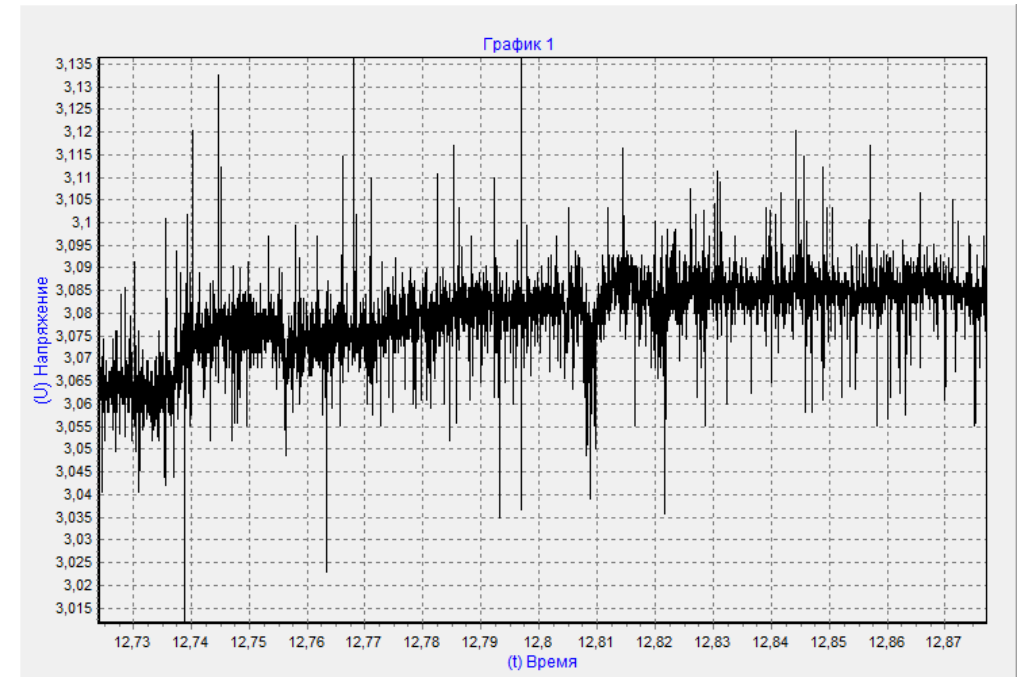
- The assembled system records the voltage change only in the sensors installed horizontally in the samples, while very strong noises are observed on the voltage change graph;

- The assembled system responds to the output of the embedded sensor. With proper tuning, it is planned to improve the visibility of the results obtained.

Figure 3.15 shows graphs of the stress-strain state of the test specimen and the voltage change of the strain gauge system for specimen No. 1



A)



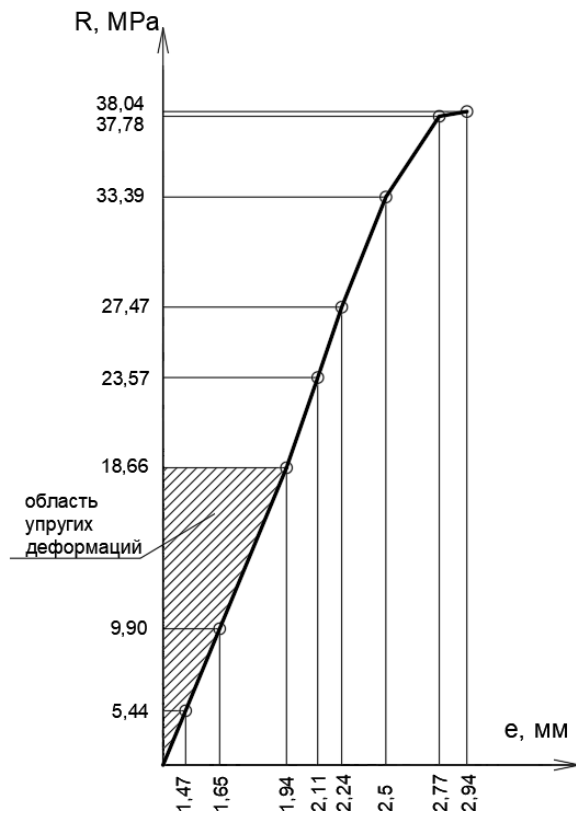
B)

A) – Graph of the stress-strain state of the cement stone sample, built according to the data from the press PGM-500MG4A;

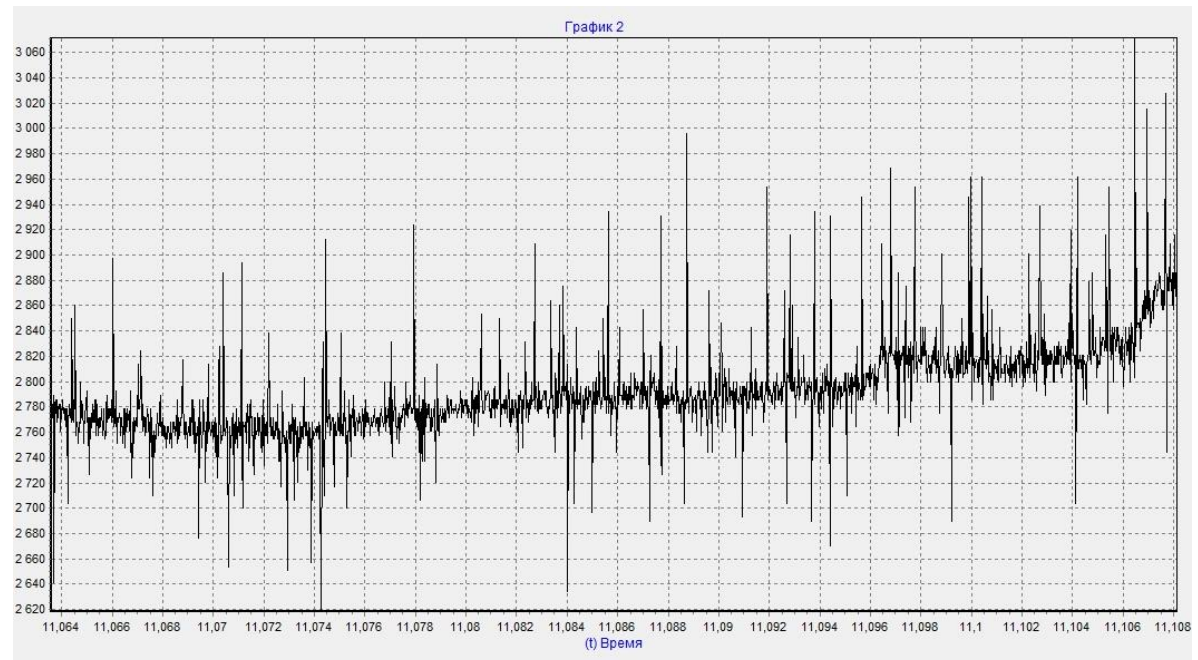
B) – Voltage change in the monitoring system over time, built according to the readings of the embedded sensor using the "PhyZModule" software

Figure 3.15. – Stress-strain change of the cement stone sample No. 1 in two variants

Figure 3.16 shows graphs of the stress-strain state of the test specimen and the voltage change of the strain gauge system for specimen No. 2



A)



B)

A) – Graph of the stress-strain state of the cement stone sample, built according to the data from the press PGM-500MG4A;

B) – Voltage change in the monitoring system over time, built according to the readings of the embedded sensor using the "PhyZModule" software

Figure 3.16. – Stress-strain change of the cement stone sample No. 2 in two variants

The nature of the destruction of cement stone samples with embedded sensors inside is shown in Figure 3.17:

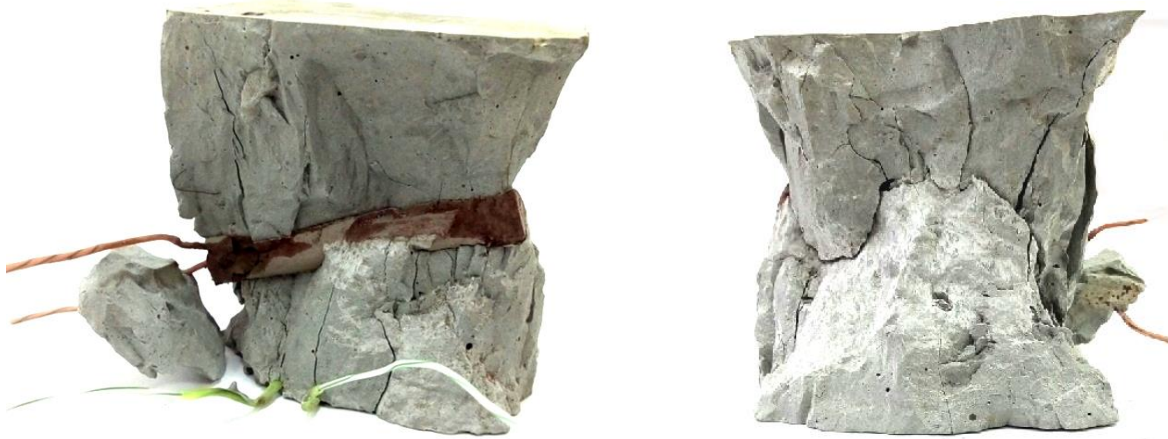


Figure 3.17. – Destroyed sample of the tested cement cube with an embedded sensor inside

The figure clearly shows that the embedded sensor fell into the area of the main crack development, thereby deforming along with the structure of the cement stone sample.

In the future, it is planned to link the results obtained on this installation with the capabilities of computer modeling for subsequent visualization and analysis of the ongoing structural changes in the body of the studied cement stone. By improving sensors and installation for monitoring the stress-strain state of cement composites, we will be able to prevent and prevent possible collapse of concrete and reinforced concrete structures.

Conclusion by chapter

1. To determine the stress-strain state of the cement stone sample, it was decided to use the tensometry method. The first prototype of a embedded strain gauge transducer was constructed;
2. The strain gauge system as well as the embedded sensor have been improved in accordance with the performance requirements;
3. The first tests of the improved strain gauge unit were carried out using the new design of the embedded sensor and the “PhyZModule” software.

4. COMPREHENSIVE EVALUATION OF CEMENT COMPOSITES RESOURCE USING THE COMPLEX METHOD: VIRTUAL MODELING, EMBEDDED AND ACOUSTIC SENSORS

4.1 Virtual simulation of a cement stone internal structure

The formation of contacts in large-porous concrete occurs during the laying of a concrete mixture, when the aggregate grains come together, up to their direct contact, the layer of cement paste enveloping the grains is displaced and formed a contact zone, which cross-section is amenable to analytical determination. The greater thickness of the enveloping layer – the larger contact area.

As noted in Chapter 1, in a cement paste, cement particles can be likened to aggregate grains in large-pore concrete. The role of the enveloping layer of the cement paste around the grains in this case is played by the shells of new formations – the products of hydrolysis and hydration of cement minerals [39]. However, the analogy in the formation of the structure of cement stone and large-pore concrete is not unlimited. It takes place immediately after the hardening of the cement stone, and subsequently, with further hydration of the cement, it can be disturbed, since with an increase in the volume of neoplasms, the pore structure can change.

To simulate the microstructure of concrete was used Virtual Concrete and Cement Testing Laboratory (VCCTL) was used [50]. This program was developed by the National Institute of Standards and Technology (NIST), USA. The program models 3D - microstructures of cement systems and allows predicting the final properties of the resulting composite. The hydration of these microstructures can be modeled according to different hardening conditions (Figure 4.1.), and the resulting hardened material can be analyzed for a number of properties, including linear elastic moduli, compressive strength and relative diffusion coefficients. 3D - packaging of small and large aggregates in mortar and concrete mixtures can also be created.

The authors decided to create a virtual model of the previously used cement composite structure, presented in paragraph 3.3.3 and 4.2. According to [40], it was selected the cement with coding 113b as the cement data file, which corresponds to the characteristics of the cement of the Belarusian Cement Plant. In addition, a three-dimensional packaging of cement stone was created by combining three planes into one cube. The final structure is shown in Figure 4.1.

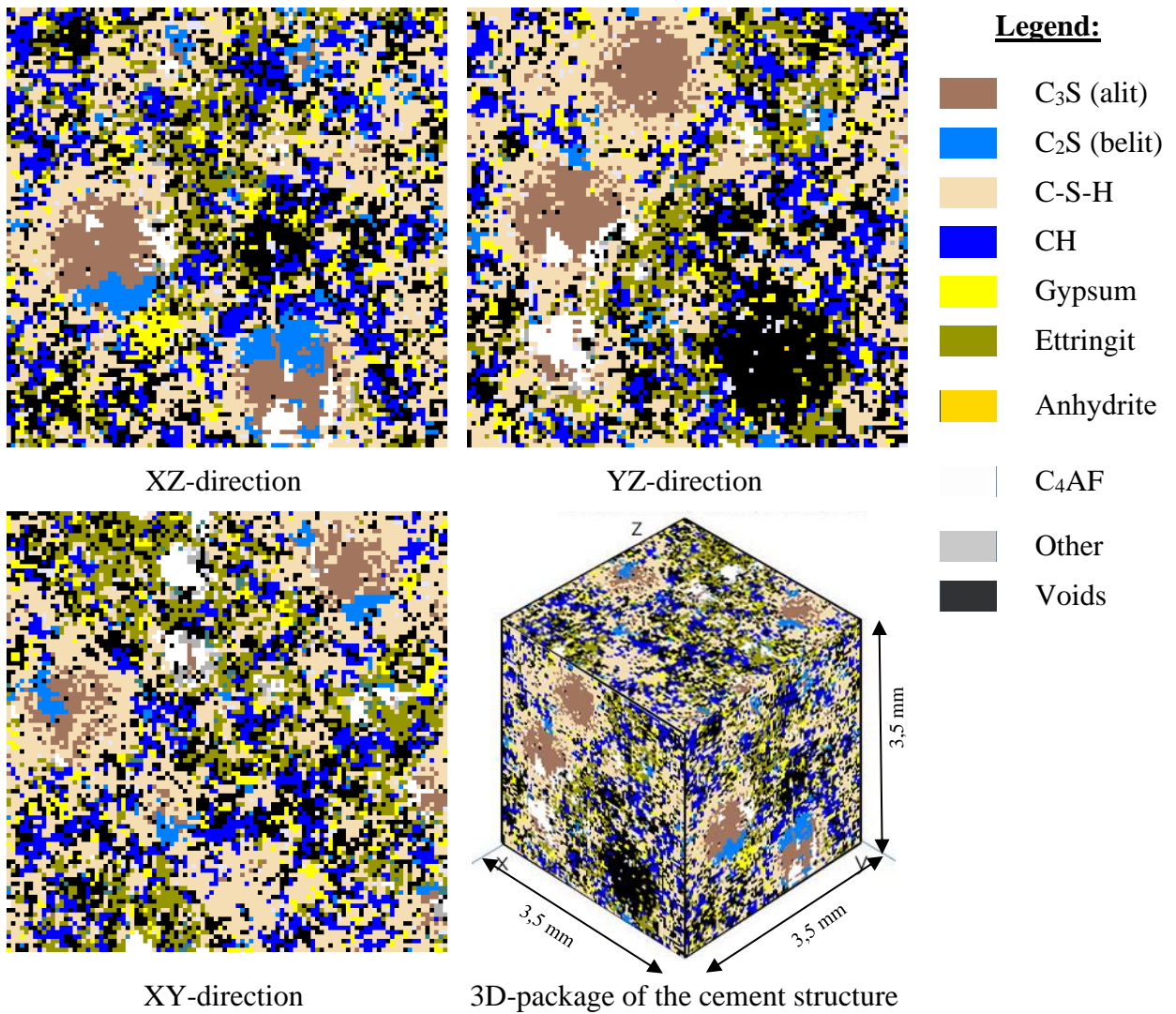


Figure 4.1. – Virtual model of the cement stone (after 28 days)

At this stage, with help of the VCCTL program, the authors obtained initial data for further modeling in software systems such as Ansys, SolidWorks, etc. The studies carried out in paragraph 3.2 should be supplemented by the results of computer modeling, which will give a broader picture of the processes occurring in concrete structures and will allow the optimization of the already obtained data, taking into account their structure at various levels of the organization. Further tests are planned in accordance with the most promising areas of concrete modeling.

Also, in the VCCTL program, was created a dynamic model of the structure evolution of the considered cement stone. For the sake of greater clarity, this model was divided into 8 sections, each of which reflects the state of the structure at a specified moment in time (step is 24 hours). This model is shown in Figure 4.2.

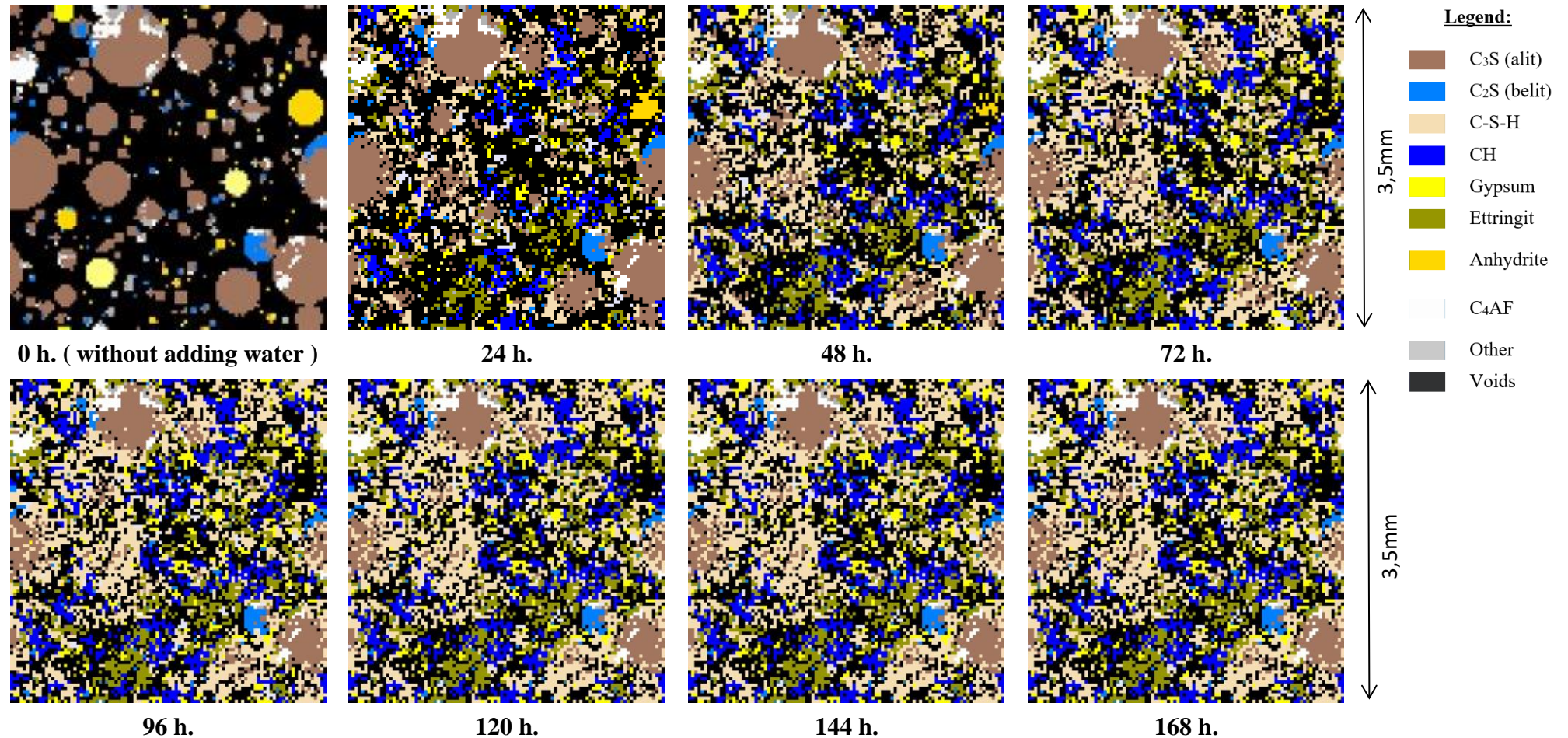


Figure 4.2. – Cement stone structure evolution during the first 7 days

4.2 Investigation of the stress strain state of cement stone using tensometry and acoustic emission methods

A cement cubes with dimensions of 100×100×100 mm, with a water-cement ratio of 0.4, were used as prototypes. This size is due to the convenience of placing several types of sensors at once, both outside and inside the tested samples. The samples were loaded with a press with a load step of ~ 25 kN. The data obtained during the tests are shown in Table 4.1.

Table 4.1. – Compression test results for cement stone cubes

Load number	Load, kN	Tension, MPa	Deformations, mm
0	0	0	0
1	22,9	2,29	0,35
2	52,3	5,23	0,47
3	78,5	7,85	0,56
4	102,3	10,23	0,68
5	128,5	12,85	0,78
6	154,3	15,43	0,89
7	178,1	17,81	1,00
8	202,7	20,27	1,09
9	229,5	22,95	1,22
10	249,3	24,93	1,32
11	280,2	28,02	1,45
12	303,7	30,37	1,56
13	332,2	33,22	1,79
14	349,0	34,90	1,89
15	–	Structural failure	

For that experiment, it was used the monitoring system presented in paragraph 3.3.2. The main feature of this system for monitoring the stress-strain state of cement composites is that in parallel to each other, mechanical stresses are monitored using embedded sensors (active method) and “listening” to the phenomena of acoustic emission with a microphone (passive method).

Further recording and classification of the acoustic emission phenomena in the cement stone sample were carried out according to Table 4.2. The dependence of the maximum AE amplitude on the mechanical load is shown in Figure 4.3.

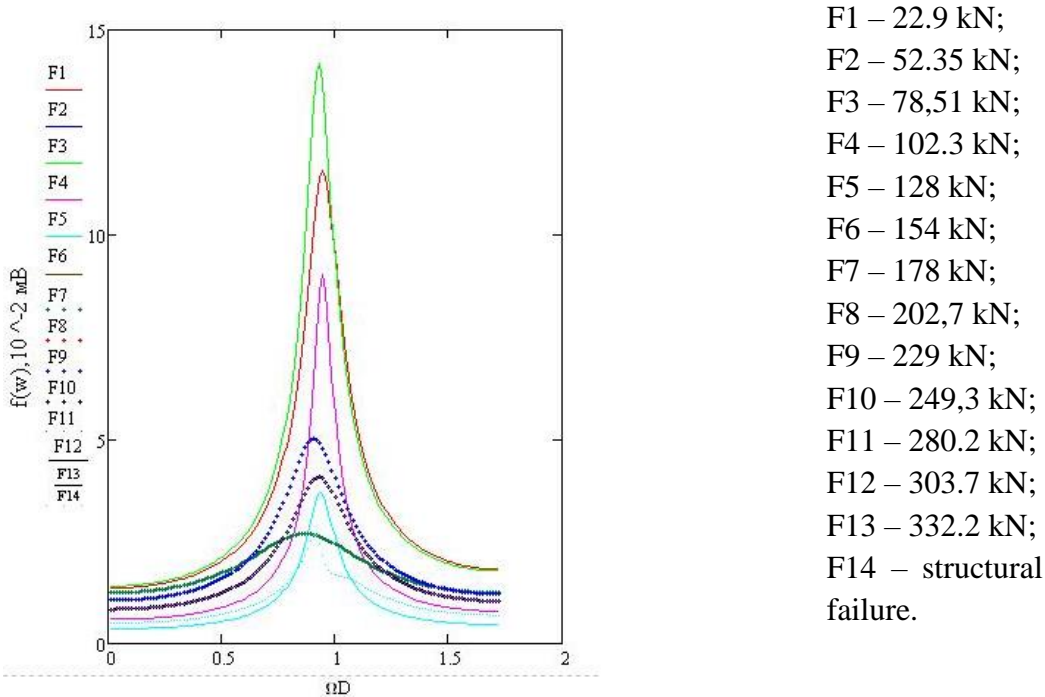
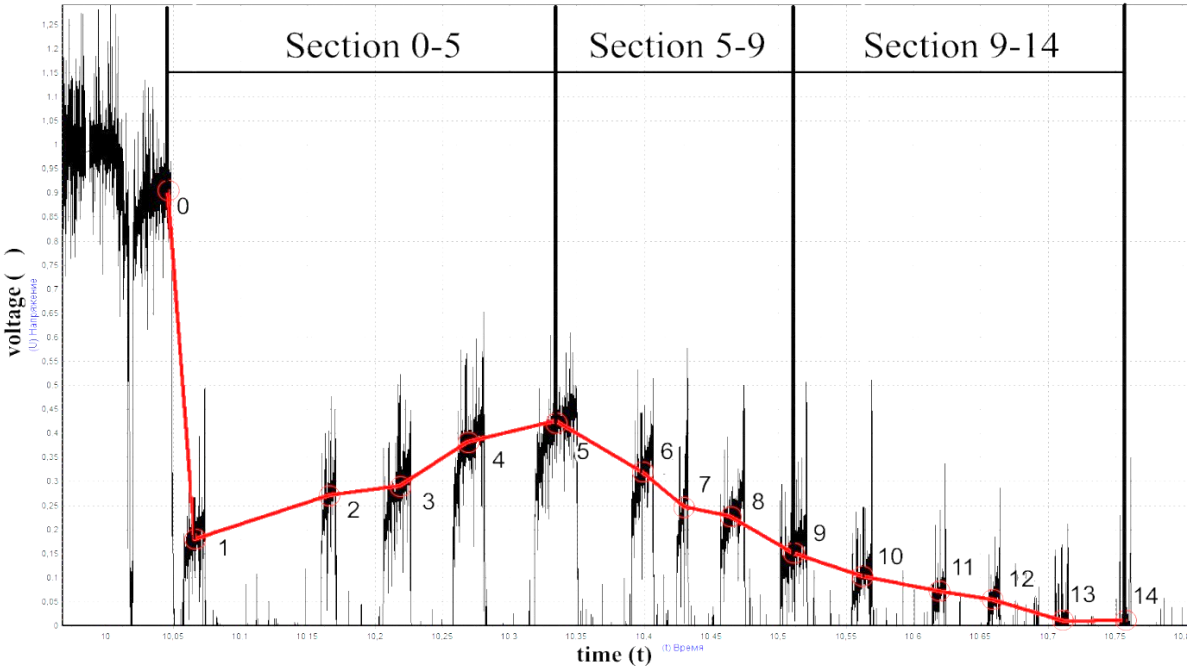


Figure 4.3. – Dependence of the maximum AE amplitude on mechanical load

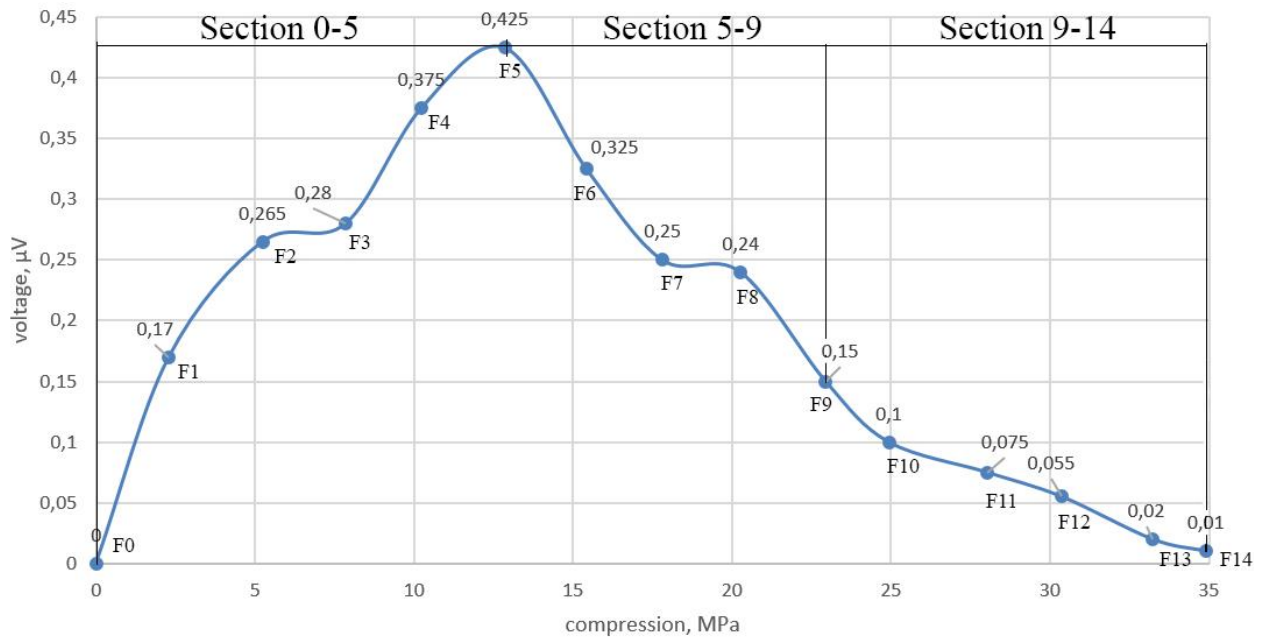
When loading the specimen in stages upward, its total deformation consisted of the elastic and inelastic components, the ratio between which at different stages of loading was different. At the initial stage of loading, weak bonds between individual structural elements are destroyed. In this case, mainly inelastic deformations will arise.

This fracture is accompanied by significant acoustic emission activity, which can be seen from the Fourier plot (F0 – F14) shown in Figure 4.3. At the stage (F0 – F5), the maximum deformation of the sample is 0.89 mm. With a further monotonic increase in the load, the ratio of less and more durable bonds between individual structural elements is constantly changing in favor of the latter. In this case, the AAE decreases. When some stress values are reached, a state of maximum compaction appears in the sample. This state is characterized by a minimum of acting and emerging defects, and hence a minimum of AAE arising under the influence of loading. This can be seen on the graph in sections F6 – F9. When the load exceeds a certain threshold value, new defects are formed and, as a consequence, the AAE grows, which can be seen in Figure 4.3 (F10). Thus, it is in the loading section, where the state of maximum compaction of the sample takes place, that elastic deformations prevail, and the AAE is minimal. According to this graph, two zones can also be distinguished, which correspond to inelastic and elastic deformations. Above 178 kN, elastic deformations prevail in the sample, which is confirmed before.

Simultaneously with the AE recording, the data obtained from the hydraulic press and embedded sensors were recorded using the PhyZModule software [15]. The data obtained during the experiment made it possible to plot the dependence of the change in the electric voltage of the strain gauge system with increasing mechanic load (Figure 4.4). The graphs presented in Figures 4.3 and 4.4 were conventionally divided into 3 stages, in accordance with Table 4.1. Each point corresponds to an increasing external load with a step of 25 kN. Point 14 corresponds to complete destruction of the tested cement specimen.



A)



B)

A) – PhyZModule screen log (voltage variation over time);

B) – Converted screen (voltage variation over mechanical compression)

Figure 4.4. – Dependence of the change in the electrical voltage of the strain gauge system (with embedded sensor) under load

Comparing the obtained graphs presented in Figures 4.3.,4.4. and the data in Table 4.1., we can draw the following conclusions:

In section 0–5, the structure compaction and the formation of microcracks in the cement sample are traced. The state of maximum compaction is taken to be point 6, which corresponds to 15.43 MPa ($\sigma_c = 0,44f_{cm}$).

Section 5–9 is taken as the stage of formation of macrocracks gradually emerging onto the sample surface. Point 10, corresponds to a stress of 24.93 MPa ($\sigma_c = 0,71f_{cm}$).

Section 9-14 is the stage of active destruction of the cement sample.

At point 14, a stress of 34.9 MPa is observed, which indicates that the specimen has reached its ultimate strength.

Thus, the use of two methods makes it possible to obtain areas of elastic deformations with a higher reliability and to avoid the accumulation of plastic ones. By improving sensors and installation for monitoring the stress-strain state of cement systems, it is possible to prevent some possible collapse of concrete and reinforced concrete structures.

Conclusion by chapter

1. The studies carried out make it possible to present the mechanism of the development of structural defects in cement systems as follows: using two types of sensors (internal and acoustic emission) allows to control the formation and further development of microdefects (cracks) in the structure of cement samples. At the same time, the created system provides for the processing of several incoming signals at once, which implies its multi-channel nature;

2. By registering acoustic emission data, the relationship between acoustic signals and deformation changes in concrete samples was determined;

3. Based on the results of the studies carried out, it can be stated that the combination of tensometric and acoustic emission methods makes it possible to track defects in concrete objects. This is expressed in receiving signals indicating the occurrence and development of a defect in real time, as well as in determining the resource of a concrete structure at any stage of operation.

CONCLUSIONS

In this work, a whole range of works was carried out to diagnose structural changes occurring in concrete. An analytical analysis of the structure of concrete and the development of various defects (cracks) in it is carried out. A hypothesis on the possible "control" of cracking in cement systems was put forward and experimentally confirmed.

Embedded sensors were designed to determine the stress-strain state of concrete samples. The manufactured sensors have confirmed their efficiency and require further improvement, as well as study of their effect on the concrete structure. It is planned to use new types of sensors and their comparison, as well as to determine the possibility of using internal sensors and their area of direct application.

A setup has been created for monitoring the stress-strain state of concrete samples using tensometry acoustic emission methods. This system will be improved and adapted to detect changes in the internal structure of cement systems.

Based on the obtained experimental and theoretical data, it is planned to carry out computer modeling of the structure of concrete and the development of cracks in it in order to obtain a broader picture of the changes occurring within the samples.

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