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Polyurea coating systems: definition, research, applications.

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ABSTRACT: The main goal of the paper is to present the current state of knowledge about polyurea coating system. The emphasis was placed here on presentation of two topics: material which is polyurea and its present applications, and a device for spraying polyurea coating systems. The work, in the next parts, focuses on explaining why polyurea is uncommon and presentation of actual applications in different industries. The paper is supplemented with a presentation of actual directions of development in research regarding polyurea coating system.

Keywords: polyurea, coating system, elastomeric polymers, energy absorbing materials

1. INTRODUCTION

The ongoing raise in requirements for the engineering and construction structures is leading the development and discoveries of state-of-the-art, modern construction materials possessing extraordinary parameters. Polyurea is one of them. It has apparently found applications in construction field, both in realization of new engineering projects and renovation and maintenance of the existing ones. It is its broad set of extraordinary properties that gave the material such a broad area of applications, namely the high durability and strong resistance to atmospheric, chemical, and biological factors.
Polyurea, also known as polyurea elastomer, is created as a result of reaction of two components: isocyanate and synthetic resin blend. Combination of the two takes place in high temperature and high pressure conditions with appropriate ratio of the abovementioned ingredients.

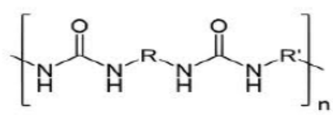

Fig.1 Chain structure of the polyurea [2]

Polyurea is a product of a reaction of polyamine and isocyanate where material of chain-type structure is created which consists of "n" molecules which are strongly combined (Fig. 1). Chain structure of polyurea makes the material highly durable and elastic and those properties cause that it finds myriad of applications in construction field.
The original application of polyurea was ballistic systems and devices as it is capable of absorbing energy. Consecutively, polyurea found further applications in engineering constructions given the aforementioned properties. It is used as hydroisolation coating for industrial floors, or as strengthening coating for steel and concrete.
This elaboration focuses on presenting polyurea as construction material given its extraordinary properties which characterize it. Naturally both advantages and disadvantages of selecting the material have been taken into consideration. Furthermore the paper is a summary of research on the material to date. The future directions and areas of use are presented as well.

2. APPLICATION MANNER

The application of polyurea on the isolated surface is a very complex process. It consists of three technological stages: preparation of the surface, mixing of the components, and application [2].

2.1. Surface preparation

The preparation of the surface is the most essential as far as the application of the material is considered. Particular attention should be devoted to checking if the surface is clean; dry; free of oil, grease, or free particles; and other substances which could have worsened the adhesion to the surface. If the surface contamination or free particles has been detected, either blast cleaning or sand-blast cleaning can be applied in order to clear the area. Oil stains or other contamination should be removed using appropriate chemical agents. In many cases appropriate priming paints are used in order to improve the adhesion. After such activities it can be reliably stated that the material coating will be firmly attached to the surface. It should be emphasized that the preparation of the surface is the most important stage in the process and the resulting quality of the material depends on it in the greatest extent.

2.2. Mixing the components

Polyurea is material consisting of two components. In order to apply the system, therefore, an appropriate set, capable of creating the desirable conditions regarding the temperature and the pressure, has to be used. The mixing of the components takes place in a hot environment using a special pneumatic or electric device used in application of two-component coating.

The precision of mixing and dosing the components plays a prominent role in the spray showering process of polyurea. The parameters of spraying (temperature and pressure in the device) have to be rigorously controlled. They have to comply with the norms given by the manufacturer in the Product Data Sheet (DPS). Moreover the appropriate voluminal and weight ratios of the components have to be continuously controlled before and during the process of spraying. Above everything, all the parameters of the mixture should be checked for compliance with the Product Data Sheet during the process of spraying in order to obtain the highest quality of the resulting polyurea coating [2].

2.3. Coating application

The spraying of the mixture takes place on the appropriately prepared and dedusted surface. Two coating layers are recommended, the first is applied directly on the isolated surface and the second directly on the first one in a perpendicular direction to it's application. It verifies the fact that the coating will be fully leakproof and without welds [2].

2.4. Device for spraying polyurea coating system

The application of the system takes place using special set of machines called aggregates capable of generating pressure of 120 bar ÷ 210 bar and resin the temperature up to 65^0C ÷ 80^0C. The machines are pretty complex due to the fact that they have to generate the abovementioned, high values of the parameters. Additionally they provide means of control for pressure and temperature of particular components in real time. A great number of sensors are placed in key parts of the device which gives the operator the possibility of full control over the mixture parameters [2-3].

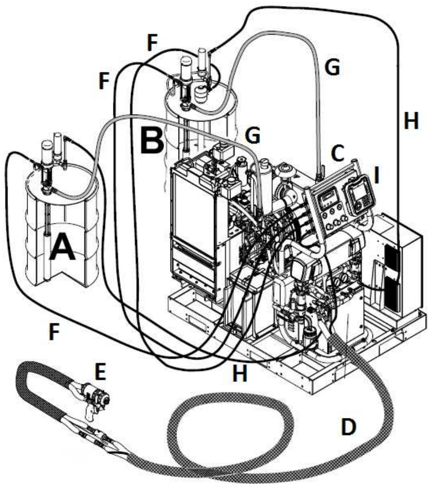

Fig.2 Diagram of a typical device used for polyurea spraying [3]

A typical diagram for a set (aggregate) of machines used for spraying was presented above. Such a device is usually used for spraying of polyurea coating or polyurethane (PUR) foams (Fig. 2). The device is an integrated device having its own combustion engine, an electricity generator, and an air compressor. It allows for complex control over all the parameters of the mixture in real time from one place [2-3].

A typical device used for polyurea coating spraying (Fig. 2) consists of [3]:

A – barrel with polyaminate component,
B – barrel with polyIsocyanate component,
C – reactor feeder (the place where high pressure pumps with heaters used to provide A and B ingredients are located),
D - heated hose (a hose equipped with heaters used for maintaining an appropriate temperature of the ingredients),
E - spray gun (a device where ingredients A and B are mixed and then instantly sprayed onto the surface at a very high pressure),
F - hoses providing air (the hoses providing air for the pumps and the stirrer),
G - hoses providing the ingredients A and B to reactor feeder,
H - recirculation ducts (used for moving ingredients A and B around heaters),
I - main control module of the device.

The presented manner of polyurea coating application is a general description of a very complex process of system application. It is worth remembering that every manufacturer of the material is under an obligation to provide an appropriate product data sheet and a manual for using the product. A detailed set of information regarding the parameters for the mixture, a manner of surface preparation, and system application can be found in the both documents.

3. ADVANTAGES AND DISADVANTAGES

Polyurea is construction material which, as any other product, has both strengths and weaknesses. However, this particular one has undeniably more strong points of interest of civil engineering which makes it more and more popular within the construction branch. The advantages and disadvantages of the two-component polyurea system as hydroisolation coating for steel or concrete have been presented.

2.1. Advantages:

Polyurea is material which is phasing out traditional methods used in hydroisolation of surface, protection of steel and concrete, and manufacture of industrial floors. This phenomenon is clearly connected with the advantages of the material presented below [1-2]:

- great resistance against water and humidity action,
- high resistance to aggressive atmospheric factors such as UV radiation,
- possibility to use in contact with drinking water,
- possibility of arching metal cracks,
- high resistance to mechanical damage,
- perfect mechanical and durability parameters,
- very high elasticity of the material,
- leakproof coating without welds,
- ease of application onto any surface,
- very good adhesion to most construction materials,
- very high chemical and biological resistance,
- high resistance to sudden temperature changes.

2.2. Disadvantages:

Polyurea coating is not without weak points which contribute to the fact that the technology of spraying polyurea on surfaces is relatively uncommon in construction field. The main weakness of such coating is state-of-the-art technology and complexity of the system which constitute the main weak points of the material [1-2], and the others are:

- application requires a specialized equipment to be used (a set of machines generating high temperature and pressure) which, in turn, raises the price,
- surface for the application has to be adequately prepared,
- surface cannot be too wet before spraying,
- atmospheric conditions during the spraying have to comply with specified requirements,
- quality of the coating depends, to great extent, on the preparation of the surface and staff training.

The abovementioned disadvantages limit, to some degree, the popularity of polyurea which is not as commonly used as tar board or resin floors.

It is caused primarily by the fact that specialised equipment has to be used for spraying and the process has to be carried out by adequately trained and experienced staff. There are many companies, which provide services of crating polyurea coating on the market, which further narrow the extent to which the material is known and utilised in the construction field.

4. APPLICATIONS

Polyurea coating found applications in myriad of industry branches due to its extraordinary properties. The first uses were connected with polyurea coating as safety measures against explosions and fire-arm shots, and additionally as protection for PUR foam against UV radiation. Contemporarily polyurea is material used in many branches of economy such as construction, energy, fuels, naval industry, waste industry, ballistic industry, etc. Selected, specific applications for polyurea coating, which are found around the world, are presented below [1-2]:

- military and defence, ballistic systems,
- coating layer sealing against leakage of containers dedicated to fuels and chemicals,
- securing wells in sewage systems,
- elements in nuclear power plants,
- naval construction,
- commercial construction,
- hydroisolation coating for aquaria,
- coating layer sealing and securing pipelines,
- coating layer sealing load spaces in goods wagons,
- architectonic and decorative elements,
- securing coating for steel and reinforced concrete bridges,
- floors and ceilings for parking spaces (Fig. 3),
- floors in kitchens and bars (Fig. 3),
- coating layer securing and sealing roof sheathing,
- sealing and filling joint connections welding,
- securing coating for cargo space for lorries,
- securing and sealing, internal lining of tunnels,
- securing coating for containers and pipelines in waste-water treatment plants (Fig. 4),
- securing coating in entertainment water parks (Fig. 4),
- protection for steel and concrete against corrosion on elements found in playgrounds.
- hydroisolation coating for roofs, waste-water treatment plants,
- foundations,
- securing cargo zones in ships, wagons, trailers,
- decorative elements (column speakers, playground elements, swimming pools),
- waterproof coating for irrigation channels and aqueducts,
- protective, waterproof coating for dams (Fig. 4),
- waterproof coating in containers dedicated to drinking water.

The abovementioned applications do not constitute the full set of manners in which the material can be used. Polyurea, due to its extraordinary properties, has practically unlimited applications for any surface in any economy branch in the whole world.

Fig.3 Photo of a typical polyurea sample with non-slip surface [2]

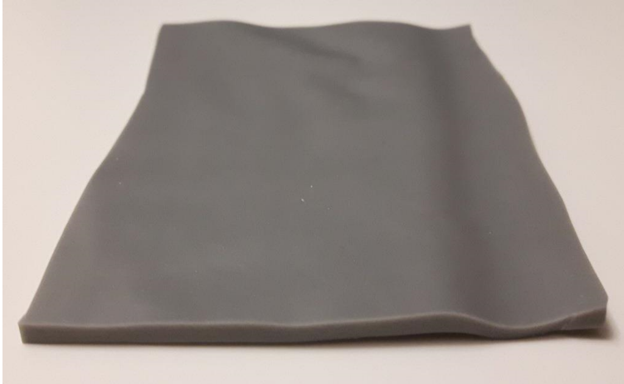

Fig.4 Photo of a polyurea coating which was sprayed onto concrete surface and next was detached from this surface [2]

5. CURRENT DIRECTIONS

Polyurea, as material of elastomer structure, has been recently popular among scientists. The reason lies in the fact that the material finds applications as an agent strengthening structures and absorbing energy in ballistic defence systems.

The paragraph below places emphasis on the presenting the scientific knowledge and research carried out on polyurea samples. It shows the areas where performed research supported the fact of high material applicability. The areas where the substance can be used include construction, ballistic, water, and many other industries.

5.1 Basic properties of polyurea

Polyurea is polymer material which is offers dynamic properties resulting from specific structure of the material. Considerable tests, as well as developed scientific procedures, which allow for unequivocal statement about properties of the polymer structure material, have been performed in the recent years

Yi J. et al., in their research [4], focused on checking the behaviour of one polyurea sample and three polyurethane ones under compression force. They work was done using a Hopkinson pressure bar (SHPB) system. An analysis of the results unveiled a visibly nonlinear, stress-strain relationship which greatly depended on the strain rate.

The next elaboration, on the part of Sarva SS. et al. [5], was devoted to an analysis of behaviour for one sample of polyurea and one of polyurethane for a relatively broad strain rate range: from 10^{-3} do 10^{4} s^{-1}. In their research [5], Sarva SS. et al. used Zwick screw drive mechanical tester for low strain rate ($10^{-3} \div 10^{-1}$ s^{-1}), an enhanced servo-hydraulic axial testing machine (MTS 810) for medium strain rate ($10^{0} \div 10^{2}$ s^{-1}), and two configurations of Hopkinson pressure bar (SHPB) for high strain rate. Sarva SS. et al., based on the results of the performed research [5], noticed that the stress-strain curve for polyurea changes from characteristics exhibited by rubber-like material for low strain rate to leather-like for high strain rate.

Most of the researches focus their attention on properties of polymer under compression stresses which was signalled by S. N. Raman et al. in their work [6]. They presented results of an experimental programme taken in order to carry out analyses of polyurea behaviour under tension for increasing speed of strain: from 0.006 to 388 s^{-1}. S.N. Raman et al., in their research [6], used two systems for the purpose of the studies: a MTS servo-hydraulic machine and Instron high rate testing system. The above elaboration is only a part of a more complex project started by the authors S. N. Raman et al. [6] in order to define specific properties of polyurea samples for low, medium, and high strain speeds. The researchers S. N. Raman et al. [6] focused on one polyurea sample. Their main assumption was to provide necessary data which could constitute a basis for calibration of material model used in software utilising a finite elements model such as ANSYS® AUTODYN®. In the analysis of the results [6], the authors emphasised the fact that polyurea could be described as material which is either linearly elastic and depends on the strain, or uniform; one of the main discoveries in the work [6] was the fact that elasticity modulus of the material increases with the strain speed of a sample. The researchers managed to describe the impact of the strain speed on elasticity modulus and plasticity boundary of the polymer based on the results obtained using dynamic increase factor (DIF), for which a definition was proposed in work [6].

The next paper of D. Mohotti et al. [7] was devoted to research on polyurea samples for high strain speed. In their experiment D. Mohotti et al. [7] used INSTRON® VHS 8800 device which was utilised in carrying out research on polyurea samples Eraspray ESU630D at high speeds produced by Era Polymers Pty. Ltd., Australia. Based on the analysis carried out, the authors proposed a new model Rate Dependent Mooney Rivilin (RDMR) allowing for prediction of nonlinear, hyper-elastic behaviour of polyurea; the definition of the model was given in an article [7]. The main advantage of the proposed model (RDMR) is that only one set of material parameters for one speed of strain is required for the presentation of the material behaviour. The values for other parameter sets for other speeds are calculated automatically within the RDMR model. Such a model will surely simplify and make the simulations more efficient. Additionally it can find applications in calculations using finite elements methods such as LS-DYNA® or ANSYS®.

Latter efforts made by the researchers focused on defining interaction of polyurea with other materials, and also on impact of temperature on the properties and the structure of the substance. Arunkumar T. et al., in their work [8], devoted attention to a phenomenon of polyurea adhesion to steel. They used AISI 1018 steel which offers a good trade-off between strength, elasticity, and high mechanical characteristics. The trials were carried out on steel samples covered with polyurea coating of three different thickness values (1 mm, 2 mm, and 3 mm). The spraying was done at a distance from steel equal to 50 mm. The trial consisted of three tests:

- **scratch test:**
  A test carried out in order to determine the critical load, which is related to coating adhesion. It was performed on samples of 50 mm x 50 mm. The abovementioned test showed very high resistance of polyurea to scratching which further increased with the increase in the thickness of the applied coating.
- **bonding test:**
  The test was carried out in order to estimate the connection quality of the tested materials. A sample of 50 mm x 50 mm was covered with polyurea coating on only one side. Next the critical tensile force, which would tear off the coating from the steel sample, was being probed during the test. The test unequivocally showed that the value of the force needed to tear the coating off raises with the thickness of the coating.
- **bend test:**
  The test aimed to determine ease with which the material can be bent without destroying the sample. Samples of 12.5 mm x 100 mm with three different coating thicknesses (1 mm, 2 mm, and 3 mm) were subjected to bending in a device with three support points. The polyurea coating of 3 mm thickness got separated from the steel sample. On the other hand, the other coating (of thickness 1 mm and 2 mm) showed that thickness decreased by half at the place of bending. Such a phenomenon can justify the strengthening property of the coating in the case of proper connection between polyurea and metal only.

Arunkumar T. et al. [8] concluded that, based on the performed research, polyurea can have decisive impact on behaviour of steel elements under load action. They emphasised that appropriate ground layers should be used between polyurea and steel in order to increase the adhesion of the polyurea.

Arunkumar T., in his next work [9], made efforts to determine polyurea resistance to variable temperature and fire factors. The author emphasised [9] that fire resistance of polyurea depends mainly on components which are added to the resin which was a component of the polyurea production system. Arunkumar T. [9] carried out three experiments about thermal expansion, thermal stability, and flammability of polyurea. An experiment showing thermal expansion was carried out within the temperature range from $+30^0$C to $+90^0$C. Based on the results, the author defined the thermal expansion coefficient $\alpha = 0.0119$ 1/K. The experiment constituting the verification of thermal stability was carried out for two extremely different conditions: in the first case the temperature was $+ 85\ ^0$C and the humidity was 85%. In the second the temperature was $+ 10\ ^0$C and the humidity was 10%. A sample was kept for 4 days in both cases; the model sample dimensions were taken from the ones in room temperature and room humidity. The test for thermal stability of polyurea carried out by the author [9] proved that the material is very stable concerning the dimensions, even when subjected to extreme weather conditions. He also signalled that the thickness of the coating was the most variable parameter for both cases. The last test constituted checking the flammability of the material (research on three samples). The author stated, based on the obtained results [9], that polyurea is flammable. During the test a sample of 12.7 mm width and 2 mm thickness was burning at a rate of 35 mm/min. In this context the scientist decided to verify the flammability of composite material in form of a steel sheet coated with polyurea. Arunkumar T. [9] found that resistance to flames of composite material is considerably higher than the one of polyurea alone. Furthermore, the fire gets extinguished by itself which makes the use of polyurea with steel sheets more justified.

Thirumal M. et al., in their work [10], focus on determination how phosphorous oxidation states, in chemicals based on phosphor which decrease flammability, influence thermal properties and flammability of polyurea and epoxide resin. The authors utilised three different states of phosphorus oxidation [10]: phosphite, phosphate, and phosphine. The oxidised phosphorus was added to epoxy resin in every case (1.5% by weight was added). The scientists were adding the oxidised phosphorus stirring it at a uniform rate with a mechanical stirrer used for Isocyanate (in the case of the polyurea) or diamine (for the epoxy resin). Next the authors carried out a series of experiments [10] in order to determine how an oxidation state impacts properties concerning flammability of polyurea and epoxy resin. The research consisted of, among others, thermal stability test (thermal analysis of the samples), cone calorimeter test (an analysis of heat release rate), thermogravimetric analysis (an analysis allowing for composition determination of gasses released during thermal destruction of samples). The analysis of the results led to one main conclusion [10]: the introduction of oxidised phosphorus into a mix of substances, both with polyurea and epoxy resin, significantly improves their thermal stability properties and resistance to fire. Thirumal M. et al. [10] highlighted that in the case of polyurea it is phosphorate in form of phosphate (Triphenyl phosphate), rather than phosphite or phosphine, that is more effective in improving the fire resistance properties. The results were not as good for the other types of phosphorate.

5.2. Ballistic systems

Polyurea as elastomer construction material has recently attracted considerable attention of scientists as far as ballistic systems are concerned due to it's ability of absorbing energy.

Initial trials of polyurea application in ballistic defence systems consisted in strengthening brick walls against a shock wave from an explosion. J. S. Davidson et al., in their work [11], presented results of three ballistic tests which tested brick walls coated with polyurea. Out of 21 potential polymers, which had been taken into consideration, pure polyurea was selected for the experiment due to its durability, flammability, and price when compared to other polyurea materials. An additional advantage of pure polyurea is the fact that it is relatively commonly used in shipyard industry as internal lining for fluid or loose material containers. J. S. Davidson et al. carried out three ballistic tests [11] using samples in form of brick walls of dimensions 2.24 m x 3.66 m fixed in steel frames. In tests 1 and 2 the wall panels were coated with polyurea only internally, and in test 3 one panel was coated both internally and externally. The chosen amount of blasting material used in the ballistic trials created the maximum pressure on a wall of 393 kPa which consecutively destroyed the not strengthened wall. In test no 2 the pressure resulting from the explosion was 1 640 kPa and all the walls were subsequently destroyed, while in test no 3 the pressure was 480 kPa and only the not strengthened walls were destroyed. J. S. Davidson et al. in [11] clearly state, based on the performed tests, that the application of coating on only one side of a wall can effectively increase its resistance against shock wave. It was signalled a few times [11] that the most injuries which occur during an explosion is not caused by the shock wave itself, but rather by structure fragments. During the tests the coating of polyurea significantly limited the number of fragments therefore increased the overall safety during a blast.

J. S. Davidson et al., in their elaboration [12], focused on depicting damage and failure mechanisms observed on 12 brick walls which had been strengthened with polyurea before the subsequent 7 ballistic tests. They also intended to discover the maximum efficiency for polyurea coating application as a way of strengthening brick walls. The elaboration [12] is a continuation of a research project described in work [11]. J. S. Davidson et al., in their elaboration, explained that failure mechanisms and damages caused by a shock wave are very complex not to mention the fact that they depend on maximum pressure, characteristics of blast impulse, and wall support conditions which create difficulties in an unequivocal determination of the failure mechanisms. They also presented results of tests with holes for windows and doors, where it was concluded that the effectiveness of the coating for walls is comparable with the one for walls without holes in the elaboration [12]. J. S. Davidson et al. presented their findings in their work based on the performed tests [12]:

- A thin coating in form of polyurea sprayed on internal surface of walls is enough for creation of secondary load-carrying structure minimizing the number of fragments from the destroyed wall.
- Adhesion of the coating to the strengthened wall is a very important issue when applying the system. It has to be so high that the coating would not be torn off the internal wall surface during the blast.
- It was noted in a few ballistic tests that the failure mechanism of a wall consists in a formation of a secondary load-carrying structure which resembles an arch, that is to say, a membrane of polyurea forms a support structure in the form of a tight arch which is attached to the steel frame to which the brick walls were fixed. The above insights suggest application of rigid supporting structures around walls (steel frame) in order to form an arch during a blast.

To summarise J. S. Davidson et al. proved in their research [12] that coating of polyurea is efficient as far as strengthening walls against shock waves is considered. The authors noted that the technology of spraying polyurea should be developed in direction of increasing ease of use and in direction of developing polymers for applications of designing buildings and devices which are resistant to explosions and blasts.

Considerable efforts connected with use of polyurea as a mixture with other materials as composite protecting against shock wave and other ballistic-related effects were made by A. Tekalur et al. They presented [13] results of experiments in their work. During the experiments, the resistance against shock wave of composite materials was studied. Two types of substance had been selected: polyurea (PU) and vinyl ester E-glass (EVE). In their experiment [13], S. A. Tekalur et al. used a shock tube which possesses an advantages of possibility to control the process which spurs problems in traditional ballistic trials. A shock tube consists of long, rigid cylinder divided into parts for high and for low pressure, physically divided by a membrane. In reality no materials are burnt in the tube while the destruction of the sample is caused by pressure caused by sudden change in pressure of gasses. S. A. Tekalur et al. used two types of samples in their experiments [13]: I – 3 mm EVE + 6 mm PU + 3 mm EVE and II – 3 mm PU + 6 mm EVE + 3 mm PU of dimensions 0.23 m x 0.102 mm. The samples were fixed in a device with their two shorter edges. The evaluation of the samples after the test was done using visual inspection, microscope inspection, and analysis of recordings from a high-speed camera. The main observation stemming from the experiment of S. A. Tekalur et al. [13] was a statement that the best resistance against shock wave was offered by a sample where soft coating (PU) was located between composite coating layers (EVE). Such a layout, according to the authors, exhibited more than 100% gain in resistance over a single EVE coating.

Subsequent efforts by researchers further assessed the feasibility of polyurea used as a helmet suspension-pad material. M. Grujicic et al, in his work [14], focused on application of polyurea as suspension-pad material in Advanced Combat Helmet (ACH). Advanced Combat Helmet (ACH) is currently the most common form of head protection used in the army of the USA; ACH is made with 7.8 mm thick, composite material strengthened with Kevlar, and also special silencing foam. M. Grujicic et al [14] used ABAQUS/Explicit software in order to check the possibility of polyurea use as suspension-pad material. They built a helmet model consisting of six segments representing individual materials as parts of the helmet. A model simulating human head was also created. M. Grujicic et al [14] performed a numerical analysis for two computational cases: (1) 5.2 atmospheric peak overpressure equivalent to a free-air explosion of 0.0698 kg of TNT at a standoff distance of 0.6 m; and (2) 18.6 atmospheric peak overpressure equivalent to a free-air explosion of 0.324 kg TNT at a standoff distance of 0.6 m. The authors stated [14], based on all the results, that polyurea is almost incompressible material. The results showed a significant reduction in peak pressure experienced by the brain when polyurea is used. According to the authors [14], it is high change in pressure which causes the most damages to a brain; polyurea limited the change therefore it is more preferred material as helmet suspension-pad material.

A. Samiee et al., in their work [15], presented results of a numerical, dynamic analysis of a steel plate response with and without polyurea coating to load caused by an explosion. They used steel plates of diameter 1.0 m and steel DH-36 in their elaboration for numerical analysis [15]. Three computational cases were subjected to an analysis: (1) a steel plate with coating from the side of the explosion, (2) a steel plate with coating not from the side of the explosion, and (3) a steel plate alone of the thickness equal to the surface density of the other samples (1) and (2). Moreover A. Samiee et al. carried out two types of simulation for load caused by an explosion [15]: (1) direct pressure load, and (2) indirect pressure load e.g. passing through soft polyurethanes or water. A numerical analysis was carried out using finite elements method in calculation software LS-DYNA. The main goal of the elaboration [15] was determination how casing made of polyurea would affect the behaviour (resistance) of a metal plate against load created during a blast. Based on the results from the numerical analysis [15], it was concluded that the deformations of the metal slab are significantly smaller only in the situation where the polyurea is on the back surface, the surface not from the side of the explosion (which applies in both cases of load: direct and indirect). The authors also noted that the thickness of polyurea coating is significant when the steel slab deformation is taken into consideration as well. The thicker the polyurea coating, the more visible is the positive effect of its application.

S. N. Raman et al. presented results of an analysis in their work [16] concerning behaviour of reinforced concrete RC panels covered with a polyurea coating subjected to a blast. The authors carried out an experiment [16] on three samples of reinforced concrete panels (two covered with polyurea coating and one not covered: a control sample), next they compared the experimental results with results of a computational analysis. S. N. Raman et al. used three samples of reinforced concrete panels of dimensions 1700 mm x 1000 mm x 60 mm [16] made with concrete of compression strength 43 MPa, reinforced in both longitudinal and transverse directions with one layer of 5 mm bars at 100 mm spacings, placed at the mid thickness of the specimen. Spraying polyurea coating of 4 mm was applied onto two reinforced panels in such a way that one was sprayed from the rear side of the load and the other had coating on both sides. The ballistic tests [16] were carried out in a test bunker which had been specially constructed for the test. It had been constructed with reinforced concrete panels of 200 mm thickness and concrete of compression strength 100 MPa. 1.0 kg of ammonite was used in the experiment as blasting material; the material was at a distance of 1.0 m from the studied panel. N. Raman et al. used LS-DYNA software for their numerical analysis in which, using finite elements method, they modelled panels which were identical to the ones in the experiment. The authors noted [16], based on the analysis of the results, that one of the main advantages of using polyurea as coating strengthening concrete structures against blast effects is limited fragmentation. Such coating is capable of securing elements against fragmentation which in turn can prevent the whole structure from collapsing. Additionally S. N. Raman et al. noted [16] reduction in RC panels deflection where coating had been applied and significant reduction of cracks in the concrete. The results of the experiments and numerical analyses, according to the authors [16], suggest that coating of polyurea strengthens RC panels which is even more visible in case of coating application from the side of an explosion.

In their next paper, L. Cai et al. [17] studied the effect of polyhedral oligomeric silsesquioxane (POSS) on increasing the mechanical properties of PU. Steel railcar tanks provide a promising way of storing and transporting toxic liquids, such as chlorine, which is very dangerous for human life and environment. The improvement in ballistic protection for these tanks leads to a need of developing effective techniques to prevent the leakage as well. In their experiment L. Cai et al. [17], used materials in form of polyurea which consisted of the following components: diamine component – Versalink P-1000 purchased from Air Products and Chemicals, Inc. Allentown, PA, USA; diisocyanate component – Isonate 143 L purchased from Dow Chemical Company, Midland, MI, USA; polyhedral oligomeric silsesquioxane (POSS) purchased from Hybrid Plastics Inc, Hattiesburg, MS, USA; and steel plates from TC-128 steel purchased from Clifton Steel Company, Maple Heights, OH, USA. L. Cai et al. conducted a ballistic test [17], during which a standard 0.50 calibre M33 ball was being shot into plates mounted on a support, rigid structure. The authors of the elaboration [17] used AUTODYN software for the purpose of a numerical analysis where they modelled identical steel panels to the ones used in the experiment, along with the boundary conditions, using finite element method. According to the authors [17], the results of the experiment showed that the used mixture of substances did not significantly increase the ballistic strength of the steel plates; however, the mix exhibited strong sealing properties which could lead to preventing the leakage in the tank. L. Cai et al. noted [17] that the hole resulting from performing the ballistic test with PU/POSS coating was no more than 4.5 mm, while the one after the test with a bare steel plate was 15 mm. The authors of the work [17] also stated that the computational model created in AUTODYN software yielded very similar results to the ones obtained in the experiment.

K. Ackland et al., in their elaboration [18], used experimental and numerical studies to investigate an effect of polyurea coating on blast resistance of mild steel plates. The authors of the work used materials in form of steel plates made with steel Bluescope XLERPLATE 350® in their experiment. The polyurea was made with the following components: Versalink® P-1000 and Isonate 143L®. Next, K. Ackland et al., used three samples in following configurations in their research: (1) 6 mm bare steel plates; (2) 5 mm steel plates and 7.7 mm coating; (3) 4 mm steel plates and 15.7 mm coating. A steel plate was 1000 mm x 1000 mm in each configuration (1) - (3), and the polyurea coating was on the rear side and was 670 mm x 670 mm which allowed for fixing the samples in the research site. K. Ackland et al. [18], in order to create a numerical model, used ANSYS® AUTODYN® software where they elaborated on a model of, both bare and coated with polyurea, plates subjected to an explosion effect created with 500 g of pentolite spheres. The authors of the elaboration stated [18], on the base of the experiment results and the numerical analysis, that utilisation of polyurea coating has a positive influence on blast resistance when compared to bear steel sheets of the same surface density. K. Ackland et al. highlighted [18] good consistence between the results obtained in the computational analysis with the ones from the experiments. The authors also noted the phenomenon of increase in residual plate deformations with the increase in coating thickness. It was caused, as they concluded, by temporary loosening of the steel plate coating which entailed deformations of the given plate.

D. Mohotti et al. discussed in their paper [19] the penetration of high velocity projectiles through aluminium-polyurea composite layered, plate systems. In their experiments [19], the authors use materials which are aluminium alloy AA5083-H116 and polyurea Eraspray ESU630D® purchased from Era Polymers Pty Ltd. Australia. Next D. Mohotti et al. [19] used four different composite plate configurations of dimensions 200 mm x 200 mm and thickness from 16 mm to 34 mm in their experiments. Numerical simulations in this paper [19] have been performed using advanced finite element code LS-DYNA®. D. Mohotti et al. indicated [19] that the energy absorption of the polyurea coating was determined by its ability of reducing residual velocity. They based these conclusions on analytical, numerical, and experimental results. Polyurea exhibits good capability of reducing residual velocity while acting as an additional shield against flying particles. The authors indicate [19] that the proposed model created in LS-DYNA® software showed greater accuracy in predicting the complete penetration process.

5.3. Strengthening steel and reinforced concrete objects

Polyurea, given its extraordinary parameters and a relatively easy manner of application even in hard to reach places, drew attention of civil engineers as modern construction material.

D. J. Alldredge et al. demonstrated [20] a potential use of polyurea coating as structural strengthening manner for frames and connections in a traditional, wooden rafter framing. A load test was carried out on a light frame which simulated rafter support on a rafter plate. An ordinary frame and one with „hurricane tie" (a flat bar strengthening the connections) were used in the test. The aim was to define how polyurea coating affects carrying capacity of an analysed connection. Two types of polyurea were used in the experiment: (1) a black version having a relatively large elongation (800%), low elastic modulus (179MPa) and tensile strengths (16.0 MPa); and (2) a white version having relatively low elongation (200%), high elastic modulus (483 MPa), and tensile strength (15.2 MPa). The thickness of the coating having been sprayed on the sample (connection) for both cases was from 2.0 to 2.4 mm. Further D. J. Alldredge et al. [20] used a 98-kN-capacity MTS testing machine in their experiment which allowed for application of force causing tear of connection. The force was applied at a constant speed corresponding to displacement of 1.27 cm/min. D. J. Alldredge et al. stated, based on the results of the experiment [20] that the use of polyurea coating in each studied case decreased the failure risk and considerably increased connection carrying capacity. Additionally, a greater force should be used in order to destroy a connection after polyurea coating application for every possible case. The difference was even 800% in a few cases better than in the case of a connection without coating. According to D. J. Alldredge et al. [20], the manner of destruction can be controlled using polyurea of different parameters, and the results show that the strengthening of traditional, wooden frame structures can be considerable. This fact, along with other parameters of polyurea coating such as protection against flood and corrosion, supports popularisation of polyurea as a strengthening coating layer.

Considerable efforts were made in order to define the best composition of the mixture which would allow for obtaining the best parameters for a protective concrete coating. J. Feng et al., in their work [21], presented results of an experiment consisting of selecting the most optimal composition of polyurea mixture in order to use it as a protective coating for concrete. The authors [21] selected an optimal mixture composition based on research on coating adhesion force, concrete contact angle, and water contact angle. Next, they carried out a series of tests verifying the mechanical and surface properties of the prepared mixture. The best parameters were exhibited by the mix of hexamethylene diisocyanate (HDI) trimer, isophorone diisocyanate (IPDI) prepolymer, and a mixture of polyaspartic ester and additives (B). The authors stated, [21] during the experiments, that the best weight proportion for the mix is HDI-IPDI-B: 0.612-0.408-1.0. According to observations of J. Feng et al. [21], the composition of the mixture and polyurea presented above was characterised with strong adhesion to concrete. Furthermore, no crack or gap formation was observed under tensile forces action. The presented mixture [21] is characterised with great adhesion force to concrete (4.5 MPa), tensile strength (16.4 MPa), elongation at breaking (456 %), and water contact angle (105^0). J. Feng et al., based on a performed analysis [21], stated that the proposed mixture is an adequate material for improvement of anti-cracking and impermeability of hydraulic concrete.

Next tests of polyurea application were directed towards determination of behaviour of materials coated with the substance under forces applied at low speeds. D. Mohotti et al. focused on definition of composite material behaviour in form of aluminium plate coated with polyurea [22] under a stiff blow impact of a small object with a low speed (5-15 m/s). D. Mohotti et al. [22] focused on investigation of the out-ofplane deformation of polyurea aluminium composite plates subjected to low velocity impacts. The authors carried out experimental research [22] and next they compared the experimental results with the ones from a computer analysis using finite elements method in LS-DYNA® software. D. Mohotti et al., in their research [22], used AA5083-H116 aluminium and Eraspray ESU630D® polyurea (Era Polymers Pty. Ltd. Australia). The experiments were carried out [22] on six different configurations of samples in form of aluminium plates of thickness 3 mm or 6 mm with polyurea coating of 6 mm or 12 mm. All the samples were 300 mm x 300 mm and were fixed in a rigid way with all their edges to the test frames. D. Mohotti et al. noted good consistence [22] of numerical analysis with experimental results in case of maximum deformation of sample midpoint. The authors stated that it is a result of a realistic representation of material properties and boundary conditions in LS-DYNA® software, which allowed for predicting the real results of the experiments with good precision. D. Mohotti et al. unilaterally stated [22], based on a numerical analysis and experimental results, that an application of polyurea in combination with aluminium increases the absorption of blast energy and reduces permanent deformation of samples. In conjunction with the above, they noted that polyurea can be used as dampening material which protects structures against sudden load impacts.

In the recent years the researchers have been searching for application of polyurea coating as material strengthening construction elements and whole structures in building field. It is due to a fact that polyurea possesses very good adhesion to steel, concrete, and wood, as well as ease of use even in hard to reach places.

The next elaboration of A. E. Marawan et al. was devoted to the issue of bending and shearing [23] of reinforced concrete beams strengthened externally by spraying polyurea coating. The authors carried out their studies [23] on 16 samples - reinforced concrete beams made with concrete of nominal compression strength of 25 MPa, and reinforced steel of yield point of 400 MPa (rods of 12 mm) and 240 MPa (rods of 6 mm and 8 mm). The samples had been coated with polyurea of tensile strength 12.98 MPa. A. E. Marawan et al. [23] prepared samples in small scale (length 1.6 m) and large one (length 3.2 m) for the bending test. They also prepared samples for the shear test: 4 samples reinforced against shear in small scale (length 1.7 m), 4 samples not reinforced in small scale (length 1.7 m), and two reinforced samples in large scale (length 3.2 m). Next most of the samples (beams) - but the control one - were coated with polyurea of the following thicknesses: 2 mm, 4 mm, and 6 mm. A. E. Marawan et al. carried out the strength test [23] with a special testing frame in reinforced concrete research laboratory at Concrete Unit, Banha University. The authors stated, based on the analysis of the experimental results, that there was more ductility of beams, but above all there were fewer concrete fragments in the destruction zone. A. E. Marawan et al. obtained surprising results concerning bearing capacity of the beams [23]. The capacity of the beams under bending improved by 11.2 % in case of big beams and by 19.4 % in case of small ones; and the capacity against shear improved by about 28.2 % for big ones and about 42.5 % for small ones. With regard to the above, it was noted and stated that polyurea coating can be used as material improving carrying capacity of reinforced concrete structures subjected to bending and shear.

S. Parniani et al. [24], in their paper, focused on evaluation of fatigue and monotonic behaviour of concrete beams strengthened with polyurea coating system. The research was carried out by the authors [24] in order to define carrying capacities of bended beams coated with polyurea. Parniani et al. proposed an analytical model as well [24] which is used for numerical analysis of reinforced concrete beams coated with polyurea, both under static and dynamic load. Their research was performed on 5 reinforced concrete beams of nominal strength 35 MPa, 4 beams were coated with polyurea and 1 beam was clear of coating which served as a control bean. The beams were of 1830 mm in length. Polyurea coating of 2.5 mm and 5.0 mm was used in the research [24] which had been sprayed onto three edges of the beams: two side edges and the bottom one. S. Parniani carried out an analysis of the results [24] and stated, based on the results, that an application of polyurea coating improves capacity against bending as well as ductility of reinforced concrete beams. In the analysed case [24] the carrying capacity of the beams improved by 9.2 % in case of coating of thickness 2.5 mm to 17.4 % in case of coating of 5.0 mm.

In connection to the above, both works [23] [24] present results which indicate that an application of polyurea coating increases carrying capacity of reinforced concrete beams which further confirms the fact that the coating can be used as a strengthening layer.

Nowadays S. K. Ha et al. presented in their paper [25] structural behaviour and performance of fast-setting polyurea-urethane (PUU) lining as structural lining material for water pipes repair. The authors chose PUU material [25] because of its advantages when compared to other materials such as (1) an ability to ensure one-day return to service, (2) minimal community impact, or (3) low installation costs. S. K. Ha et al. carried out a series of experiments [25] in order to define applicability of PUU as material for quick and non-invasive pipe repairs. The authors presented and described, in their elaboration [25], results of tests such as (1) pull-off bond test, (2) hole and gap spanning test, (3) angular displacement test, (4) transverse shear test, and (5) fatigue cyclic loading test. The authors utilised polyurea-urethane (PUU) in their work [25], which was produced in Lining City Co. Ltd. in South Korea, and water-main pipes of diameter 150.0 mm and thickness 3.0 mm. One main conclusion stemmed from the pull-of bond test: dry surface impacts the most the adhesion of polyurea coating to metal. According to S. K. Ha et al. [25], PUU material passed a hole spanning test where a pipe of hole 5.0 mm sealed with PUU coating withstood water pressure of 110 MPa which was higher than the average pressure of water used in water-main pipes (which is 6.75 MPa). The angular displacement test [25] indicated that fast-setting PUU lining material exhibits more than adequate angular displacement capacity in normal using of water pipe. The transverse shear test [25] indicated that transverse shear capability of fast-setting PUU lining presents more than adequate shear resistance in order to maintain longitudinal continuity corresponding to existing, unrestrained ground movements. The last test, which was a fatigue cyclic loading test [25], indicated that fast-setting PUU lining exhibited high fatigue resistance in the range of 10^5 cyclic loadings. S. K. Ha et al. [25] found, on the basis of prior studies, that fast-setting PUU lining can be used as strengthening coating in order to repair water pipes.

6. CONCLUSIONS

Polyurea is a class of elastomeric co-polymers which possesses a unique set of mechanical properties and offers a wide range of applications in modern industry branches. Polyurea is phase-separated into nanometre size hard domains and low glass-transition temperature, soft mix which makes it really uncommon. Undoubtedly the use of polyurea coating in the last decades is widely practised in modern engineering constructions and ballistic structures. It is caused by unusual properties of the coating such as ability of absorbing energy, high elasticity of the material, scratch-resistance, or very high adhesion to practically any surface. These characteristics make the substance applicable in every kind of industry. Moreover, the polyurea ability of increasing stability of structures and elements under static and dynamic loads was proven in the presented works [4-25]. It makes the material true cutting-edge substance of the future capable of replacing the ones used contemporarily as far as improving bearing capacities of structures is concerned. The scientific research [4-25] presented in this paper allows to state that polyurea can be applied for prolonging operation of many existing engineering objects through improving their resistance against external factors (chemical and biological corrosion, or atmospheric factors). The fact that polyurea has been finding broad applications in many fields; such as durable, resistant against abrasive action and corrosion coating for tunnels, containers, and spaces for vehicle loads, and also as internal and external coating protecting buildings against explosions; for a decade further supports the above conclusions.

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