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Innovative technologies in constructions. Self-repairing concrete used in road infrastructure

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Abstract. Currently, concrete is the most widely used structural material in road infrastructure. Concrete is a sensitive material, cracks and micro-cracks may occur during operation. Although the cracking/micro-cracking of concrete does not implicitly cause structural damage, it creates a path for corrosive factors, which leads to decreased structural durability caused by material changes and reinforcement corrosion. The self-repairing ability of concrete refers to the process of closing cracks to prevent the entry of potentially aggressive agents. Concrete used in bridge construction is usually covered with a waterproof layer and a layer of asphalt mixture, which also acts as a wear layer, but which can prevent the entry of water containing corrosive ions, the natural aggressiveness of the environment or accelerated corrosion by the penetration of thawing substances etc. Road infrastructure repair works affected by degradation processes are costly, time consuming and lead to a reduction in traffic flow, by partially closing it during interventions. To overcome these shortcomings, over time, several types of concrete with self-repairing properties have been developed, based on several methods such as: pipe networks, superabsorbent polymer capsules and textile fibers, bacteria etc.

1. Introduction

The construction sector is changing at a dizzying pace, construction technology in the case of road structures, is fully driven by the need to increase productivity. In this sense, the key to success of a new era, the automation of construction processes, the robotization of works and new construction materials mark the future of the construction industry.

Every day, the construction sector generates a huge amount of information and data on various aspects, such as design and implementation costs, activities in terms of successions and the critical path, construction times, materials used and workforce dynamics. The complexity of this data and the projects themselves involves detailed customization, which makes it more difficult to make decisions and clearly generates the need for innovative systems and solutions that provide the necessary information at any time, such as feedback and recalibration of decisions.

In this sense, the construction sector needs new approaches and services that allow better planning and control for the development of infrastructure investment projects, as well as streamlining business needs in a constantly changing sector.

Aware of its importance in society, the construction sector is constantly developing innovations in smart materials and looking for new, cost-effective and time-efficient technological solutions. These innovations will allow investment organizations to increase their productivity, optimizing resources and improving compliance with deadlines and the quality of road infrastructure. Moreover, by

developing new smart green materials it is possible to reduce the environmental impact and the costs of building road infrastructure.
Technological innovation in road infrastructure transforms this sector thanks to innovative technologies such as new construction materials and innovative solutions with self-repairing properties to increase the durability of existing materials and increase the life of the investment, reduce intervention and maintenance measures and implicitly decrease operating costs.
Some technologies, already developed for a long time, are quickly gaining ground on the market, thanks to lower and lower costs. While others have successfully passed the experimental phase and today are ready to be used in industry, simplifying and innovating the construction sector, providing greater productivity and safety.
There are several significant changes that can be observed in the execution of road infrastructure works through the use of innovative materials, but this article only deals with the use of self-repairing concrete.

2. Defining concrete and self-repairing concrete as a construction material

Concrete, as a building material, is also most used in road infrastructure. Concrete is not an independent material, but a mixture of various materials. These materials include cement as a binder, water, fine aggregates and crushed aggregates or gravel.
Concrete is similar to mortars in both composition and structure. Unlike ordinary mortar, however, concrete has a wide range of applications. The size of the coarse aggregates, a specific component of the concrete, gives superior strength attributes to the concrete, which the mortar does not have.
As engineering technology developed and the performance of concrete improved, this material began to be used more and more widely. The biggest problem of concrete is its vulnerability to cracking or local damage that occurs inside the material, subject to its microscopic characteristics and external loads. The problem of material cracking is usually unavoidable due to the influence of its own weight and the environmental conditions of cracks/microcracks appearing as a result of the contraction process due to the rapid loss of water from the mixture.
In the past, the problem of concrete cracks has been a constant concern of engineering and academic circles.
The self-repair capacity of concrete has not only beneficial effects on the material durability and service life, but also on the life and safety of the entire structure.

2.1. The advantages of concrete as a construction material

2.1.1. Operating time and safety. Its characteristics allow constructions with a useful life of more than 100 years, which cannot be said for other components.
Concrete is very resistant to adverse climatic environments such as hurricanes or storms.
The fire resistance of concrete has not been matched by any other building material until the present. Here is a big difference from wood, because if a concrete building burns, it can be repaired. Wood, although there are fire retardant treatments, should be replaced with another if a fire breaks out.

2.1.2. Economy. Concrete is the second most consumed material in the world after water. Concrete components (cements, aggregates and water) are very common. This promotes the development of local industry and reduces the impact on the environment associated with the transport of materials to works. Moreover, the construction elements can be created on site or prefabricated.

2.1.3. Durability and reversibility. One of the advantages of concrete is that, when the useful life ends, it can be 100% recycled.

2.1.4. Comfort. Due to the thickness that concrete walls usually have, their thermal insulation is higher than any other material. Due to this tightness, the material favors a superior air quality inside the buildings. Concrete favors a higher temperature stability inside a building, because it smoothes the variations and makes the interior cool in summer and not so cold in winter.

2.1.5. Design. Due to its characteristics and the innovations that have been produced, concrete is very easy to handle and can be given an infinite number of shapes.

2.2. Concrete degradation situations

Among the factors capable of causing damage to concrete are the following:
Degradation caused by external agents:

- Physical attack: erosion and frost;
- Chemical attack: acids, sulphates, alkaline reaction etc .;
- Reinforcement corrosion: carbonation and chloride attack.

Intrinsic degradation of the concrete itself:

- Non-structural: contractions, retractions, expansions etc.;
- Structural: compression, traction, bending, shearing, torsion, perforation.

Degradation caused by extraordinary factors such as:

- Fire;
- Earthquake;
- Impact;
- Expansive soils;
- Landslides.

Figures 1 and 2 presents situations of degradation of the concrete road infrastructure by yielding through cracking and reducing the durability of the works.

Figure 1. Suceava Union Bridge (Source: www.stirisuceava.net). [1]

Figure 2. Sibiu - Orăștie Highway (Source: www.economica.net). [2]

Without being the premature cause of the rapid degradation of the structure, the appearance of cracks and networks of micro-cracks in the concrete does not mean an immediate structural failure. However, over time, the cracking phenomenon of the external and internal microstructure of the concrete showed a dangerous development and created the path of the corrosive agent into the depth of the concrete elements, leading to gradual degradation by corrosion of the built-in reinforcement as well as to the decrease of the load capacity and the structural stability.

3. Self-repair capacity: defining the concept

The self-repair ability of concrete is a process studied by many researchers.
Self-healing was first discovered by the French Academy of Sciences in 1836 (Lauer, Slate: 1956) [3], where it was concluded that self-healing is achieved by converting calcium hydroxide emanating from hydrated cement into calcium carbonate upon exposure to atmosphere (Hearn et al .: 1997) [4].
The self-repair capacity has been established as the ability to repair/regenerate, in part or in full, a state of deterioration in the structure of a material and therefore to improve its performance, after a factor or a combination of factors has generated the state of degradation, at the evaluated level (by Rooij et al .: 2011) [5]. Self-repair capacity is an intrinsic material characteristic, with repair/regeneration effects independent of external interventions.

The concept of self-repairing material, or material that, autonomously, has the ability to recover all or part of its properties, arises from the observation of nature. A typical example of the phenomenon of self-repair is the degradation suffered by the bark of trees or the skin of animals and humans, which heals in an autogenous way, without the need to provide an additional agent. The concept of self-repair has very significant advantages in structural materials, mainly in terms of concrete, which suffers a degradation of its mechanical properties over time. The huge maintenance costs of road infrastructure could be reduced by developing self-repairing structural materials.

4. Self-repairing concrete

Among the construction materials, concrete is the most used, so the problems of its maintenance and repair are always topical. Research to improve the performance of this material is ongoing and global. The main goal is to reduce maintenance and repair costs, which have always been a problem.

One of the disadvantages of concrete compared to other materials is the susceptibility to the formation of microcracks. This may seem harmless, but in climates where concrete is exposed to water, it can mean a significant influx of aggressive substances, which accelerates the deterioration and therefore the structural properties of the material. Self-repairing concrete can be repaired by closing microcracks. The microcracks that appear in time in the concrete surface do not implicitly cause the loss of the resistance of the structure, but they favor the penetration of harmful gases and liquids that can affect its durability.

The structure of concrete is affected by various environmental factors, such as changes in temperature and humidity, external loads etc., resulting in microcracks or damage of various shapes and sizes. This greatly reduces the load-bearing capacity, durability and impermeability of concrete materials. If not repaired in a timely and efficient manner, it will inevitably affect the normal performance of the structure, shorten its life and even cause catastrophic accidents, threatening people's lives and the safety of road infrastructure.

Due to the limitation of detection technology, it is difficult to quickly and accurately detect fine and small-scale degradation in road infrastructure. At the same time, it is difficult to effectively repair internal microcracks with conventional repair methods. To solve the problem of repairing micro-cracks in road infrastructure, improving the stability of concrete performance and prolonging the life of concrete, as well as road infrastructure projects, the development of self-repairing concrete materials and technologies has become an important area of research in construction.

The development of new and reliable concrete self-repair technologies and the in-depth research of its repair mechanism are of great importance for improving the durability of concrete materials and increasing the life of concrete structures.

The characteristics of concrete, as a material used in road infrastructure, are: high compressive strength, durability, reliability and less maintenance during its useful life.

5. Overview of self-repairing concrete research

Methods of treating concrete cracks are generally divided into active and passive treatments. Passive treatments can only repair superficial cracks, while active methods can repair both external and internal cracks.

To improve the durability of the concrete and to prevent the penetration of aggressive agents inside the concrete, passive treatments can be used consisting of covering the outside with a substance based on chemicals and polymers. Also, sealants can be injected or sprayed on the observed cracks. These sealants are generally made up of chemicals such as epoxy resins, chlorinated rubbers, waxes, polyurethane, acrylics and siloxane. Some limitations of these treatments are their low resistance to atmospheric conditions, sensitivity to moisture, low heat resistance and different coefficients of expansion between concrete and sealants.

Active treatments are also known as self-repair, self-sealing or self-healing techniques and can be activated autonomously under different conditions, regardless of the position of the crack. That is, they have the ability to activate automatically when the crack appears and can close it. At this point, it is possible to differentiate between those materials that perform a sealing function, cover the crack to avoid exposure to the environment and generally consist of passive treatments and those that have the function of repair, so that the initial characteristics of concrete to be completely or partially restored (active treatments) (Seifan, et.al .: 2016) [6]. There are different ways in which the self-healing mechanism is generated, which are mainly the following:

5.1. Autogenic repair

Autogenic repair is a process that occurs naturally in conventional concrete due to hydration of unhydrated cement particles or carbonation of dissolved calcium hydroxide (Wu: 2012) [7]. There may be various mechanisms that cause the phenomenon of autogenic self-repair, such as (see figure 3):

(a) Formation of calcium carbonate or calcium hydroxide in the form of crystals;
(b) Obstruction of cracks by the accumulation of impurities in water and concrete particles resulting from cracking;
(c) Hydration of unhydrated cement in unreacted concrete or cementitious materials;
(d) Extension of the hydrated cemented matrix to the edges of the crack. (Ter Heide: 2005) [8].

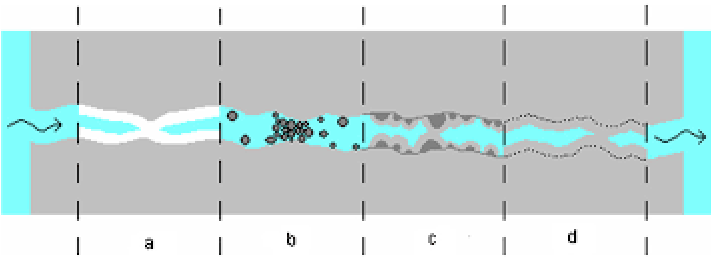

Figure 3. Possible autogenic self-healing mechanisms.

Of all these possible causes, the main mechanism is attributed to the crystallization of calcium carbonate (Edvardsen: 1999) [9].

5.2. Hollow fibers

This is the incorporation of bare fibers that contain repair components into the concrete mix. Therefore, when the concrete cracks and these fibers break, they release their contents and start repairing the crack.

The idea of using hollow fibers is to store a certain type of recovery agent inside said fibers, which in turn is evenly distributed throughout the matrix. When the damage spreads or the matrix cracks occur, under certain stimuli the fibers will break, releasing the agent inside them, flowing through the cracks and repairing them at the same time.

In studies conducted by Dry (Dry: 1994, Dry: 2000) [10], [11] hollow polypropylene fibers were used with methyl methacrylate as a repair agent, which is released when fragile fibers are damaged and as as the damage spreads, the repair agent will seal the crack. Other studies have been performed using ethyl cyanoacrylate, which have also given good results (Joseph et al.: 2009) [12]. All this work focuses on the one hand on the ability of the agent to penetrate through cracks under the action of capillary and gravitational absorption forces and, on the other hand, on the study of certain mechanical properties, such as rigidity, maximum load or ductility after the recovery period.

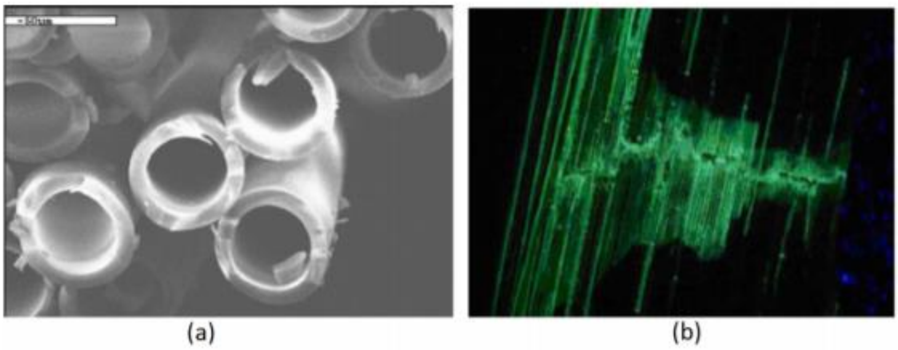

Figure 4. Hollow glass fibers.

In figure 4 hollow glass fibers are shown:

(a) Hollow glass fibers;
(b) Visual representation of the damage caused to a sheet of composite material by the action of a fluorescent liquid coming out of the hollow glass fibers (Pang, Bond: 2005) [13].

5.3. Microencapsulation

Microencapsulation consists of a technique by which self-repairing or sealing substances are encapsulated in small spheres that are released when the crack in the concrete occurs.

It is based on the incorporation of healing catalyst particles, protected in microcapsules, uniformly dispersed in the matrix from the beginning of the initial kneading stage, triggering the polymerization of the repairing agent and ensuring the closure of the crack. The curing agent remains in the microcapsule until the crack spreads, leading to the rupture of the shell of the microcapsule, which will lead to the release of its contents, which will carry out the repair process.

The difference between hollow fibers and microencapsulation is that, while in the use of hollow fibers, the agent inside is considered a separate product or a component of a product, in terms of microencapsulation, the inside of the capsule cannot be defined as a separate product, but rather it is described as a process in which certain reagents or particles are isolated to prevent unwanted reactions.

Figure 5 schematically represents the mechanism of action of microencapsulation, and in figure 6 is an image obtained by electron microscopy of a broken capsule.

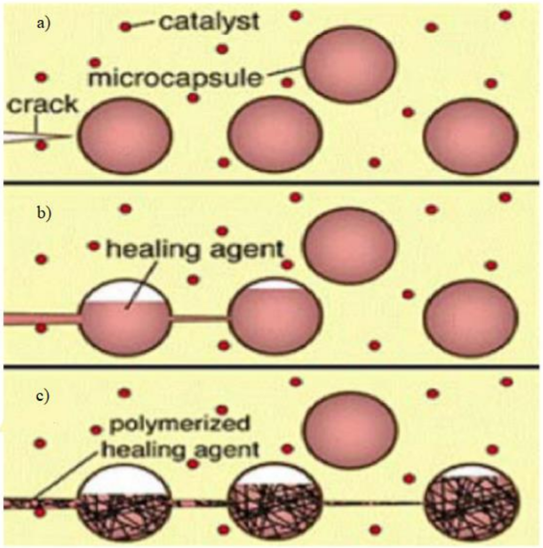

Figure 5. Figure no. 5: Basic approach of the microencapsulation model:

(a) propagation of cracks in the matrix;
(b) the crack breaks the microcapsule, releasing the repair agent through the crack by means of capillary actions;
(c) the repair agent comes into contact with the catalyst, producing polymerization and consistent crack closure (White et al.: 2001) [14].

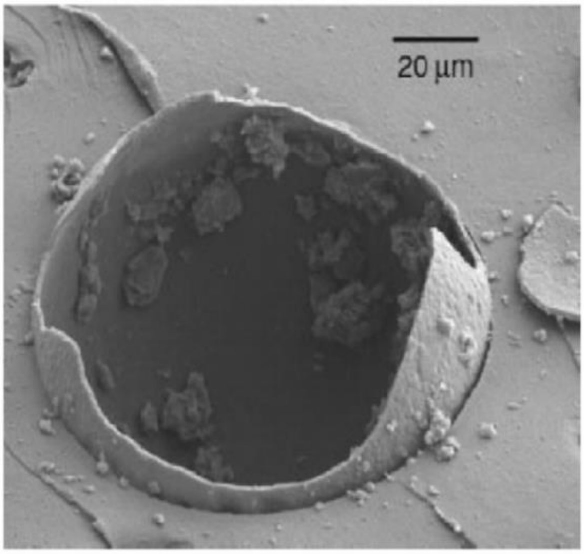

Figure 6. Image obtained by electron microscopy showing a broken microcapsule (White at: 2001) [14].

5.4. Biomineralization

Biomineralization is a process based on biological principles that mainly refers to the use of bacteria that remain latent in concrete and is activated when concrete comes in contact with moisture, requiring compounds such as calcium lactate to produce calcium carbonate and seal cracks.

More precisely, this alternative, through the use of bacteria, focuses on forcing self-repair through biological repair techniques, by introducing certain bacteria into concrete (Jonkers et al.: 2008, Tittelboom et al.: 2010) [15], [16].
The idea is that these bacteria help generate calcium carbonate CaCO3 because they produce it as part of their metabolism. The preconditions for repairing cracks through this mechanism are various, such as the concentration of inorganic carbon, the pH level or the concentration of free calcium ions, so that in order to ensure the repair of the crack, special attention must be paid to all prerequisites. Figure 7 schematically represents the process of repairing a crack using this method.

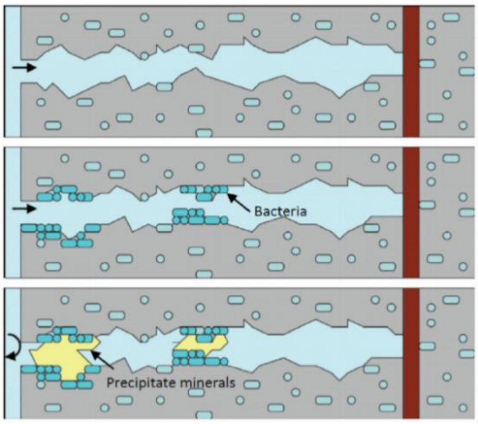

Figure 7. Schematic representation of crack repair using bacteria.

Bacteria on the faces of the crack that form are activated by interacting with water, beginning to reproduce and precipitate calcium carbonate as part of their metabolism, which seals the rupture and protects the inner armor from possible external chemical attacks (Jonkers et.al .: 2008) [15].
The ideal treatment should have quality, long life, ability to penetrate and act in successive repairs in an unlimited way (Herbert: 2012, Seifan et.al .: 2016) [17], [6].

6. Alkaline activated geopolymer binder without cement content

Currently, many research units are concerned with the development of intelligent materials with applicability in the field of construction.
Following the research carried out by NIRD URBAN-INCERC, a material with special properties was discovered that is introduced into concrete as an additive and has self-repair properties. This material is intelligent because it acts only when the crack occurs and the aggressive agent enters through the water. Contact with water causes hydration reactions and generates the appearance of hydrocomposites that fill the crack. [18]

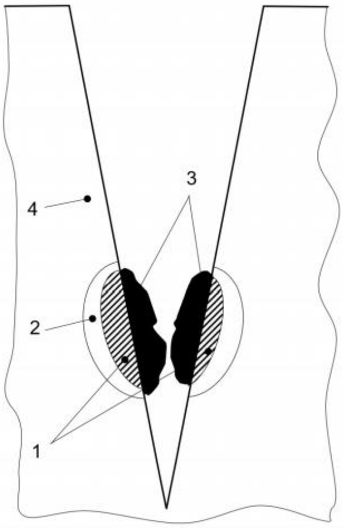

Figure 8. Graphic representation of the self-healing concrete concept by using the reactive granular material, microencapsulated. [19]

1. smart additions
2. waterproof coating
3. higher volume compounds
4. concrete

The permeability of the resulting hydrocomposites is lower than that of the mortar/concrete and thus a very good protection of the embedded reinforcement is achieved. Water access to the concrete can be prevented by using a fiberglass anti-crack layer on the asphalt mixture tread. This is an additional method of protection.

The activated alkaline geopolymer binder without cement content is an innovative material obtained initially in the form of a paste, and then, following the heat treatment, it results in the form of a hardened product. The heat treatment is done by keeping at temperatures between 50 – 80^{o}C for a period of time between 4 - 48 hours [18].

The binder has the following physical-mechanical characteristics (values recorded 7 days after preparation): apparent dry density 1200 - 1400 kg/m^3, tensile strength by bending 1,3 – 6,5 N/mm^2, respectively compressive strength 5,1 – 35,0 N/mm^2 [18].

The activated alkaline geopolymer is a binder material obtained by alkaline activation of materials rich in SiO_2 and Al_2O_3 (Al Bakri Abdullah et.al .: 2011) [20].

The raw materials used are power plant ash (class F) and alkaline activator. The power plant ash used must have an oxide composition (SiO_2 + Al_2O_3 + Fe_2O_3) > 70% and the fineness characterized as a residue on a sieve of 0,045 mm, maximum 40% [18].

As the type of ash used influences the evolution of the geopolymerization mechanism, the variation of the oxide composition, the granularity and the specific surface are taken into account.

The alkaline activator is a solution obtained by mixing controlled amounts of sodium silicate solution Na_2SiO_3 with a solution of sodium hydroxide NaOH. In the case of geopolymer materials, silicon and aluminum react with the alkaline solution, forming an alumino-silicate gel that binds the matrix to the aggregates and provides strength to the material.

The main property of these materials is the compressive strength. The compressive behavior of geopolymers varies depending on the materials used and the methods of producing this type of material (Mehdi: 2009). [21]

The activated alkaline geopolymer without cement content differs from the types of geopolymers known so far, by the fact that it uses only thermal power plant ash that is available in Romania.

The innovation gives concrete structures characteristics of solidity, durability, self-maintenance and self-repair capacity. The advantage of innovation is the use of cheap and environmentally friendly materials, local (thermal power plant ash), thus preventing the conversion into landfill waste.

7. Conclusions

Technology is one of the most prominent factors that determine the rules of competition, plays a major role in structural change, in the creation of new industries and is a great equalizer, as it can damage the competitive advantage of well-established companies and push others to the forefront.

The efficient adoption of new technologies will allow companies in the construction sector to focus on meeting the growing needs of their customers in a more personalized and faster way, which will be an engine of growth and competitiveness for companies.

Concrete self-repairing technology plays an important role in the field of civil engineering. This technology can effectively heal the surface cracks of the concrete, improve the internal structure and improve the mechanical properties and durability of the material.

Among the many advantages of using self-repairing concrete in road infrastructure are the following: reduced costs for road infrastructure maintenance and repair, increased life of structures with lower costs, cement economy by not justifying such a large number of new constructions, reduction of greenhouse gas emissions, use of cheap and environmentally friendly materials, local (thermal power plant ash), as well as reducing the consumption of non-renewable resources. The reduction of costs will be made on the basis of increasing the period between two repairs, without the safety of the structures suffering. Also, the use of self-repairing concrete will reduce the environmental problems related to the intervention works and the waste resulting from this activity.

Results obtained by NIRD URBAN-INCERC research involve obtaining a material with special properties for filming a water-reactive material that is introduced into concrete as an additive. When cracks appear in the concrete, the impermeable coating cracks and allows contact with water, which causes hydration reactions and the generation of hydrocompounds that fill the crack. The obtained

material (addition) is intelligent, acting only when the crack occurs and the aggressive agent enters through the water. The permeability of the resulting hydrocomposites is generally lower than that of concrete, so that a very good protection of the embedded reinforcement is achieved. At the same time, as additional protection, the access of water to the concrete can be prevented by using an anti-crack layer of fiberglass at the level of the tread in the asphalt mixture. This solution can be used in both repair and new works [18].
The use of geopolymer as a material with self-repairing properties embedded in construction materials causes companies with concerns in the field of road infrastructure to take into account the design and execution of concrete constructions (roads or bridges), but also for maintenance and repair operations.

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