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A qualitative analysis of technical, financial and toxicity parameters of nanocoatings to increase the aesthetics of reinforced concrete Dutch public art

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Abstract

Reinforced concrete Dutch public art is deteriorating due to environmental influences, reducing material properties and human devastation. Deterioration of concrete causes cracks, dirt and color change on the surface, which damages the view of concrete public artworks. Koninklijke Oosterhof Holman is an integrated infrastructure company, an expert in concrete and interested in applying nanocoatings on reinforced concrete Dutch public artworks. Therefore, an overview is created to compare the nanocoatings with a currently used epoxy coating on technical, financial and toxicity parameters in a qualified rating system. Based on literature research, results indicate that all nanocoatings score higher on technical parameters than the epoxy coating. However, not enough information is available on the financial and toxicity parameters of nanocoatings to accurately access the applicability on reinforced concrete Dutch public artworks. As the qualified rating system contains insecurities and uncertainties in the rating process, it is too early to apply nanocoatings on reinforced concrete Dutch public artworks for Koninklijke Oosterhof Holman. To summarize, this research serves as an initial starting point on the applicability of nanocoatings to reinforced concrete Dutch public artworks and further research on industrial applications is required.

Contents

1 Introduction: the interest to apply nanocoatings on reinforced concrete Dutch public artworks

Outdoor art is deteriorating due to environmental influences or they are at the end of their technical life. Regular maintenance is required to keep surfaces clean from vegetation, dirt and graffiti, which results in high restoration and cleaning cost. However, this does not prevent artworks from deterioration on the long term, because material properties reduce over time due to environmental influences (Graziani et al., 2016). This causes cracking and color change on the surface, which destroys the view of public art (van Burkom et al., n.d.).

A coating is a method to modify the surface properties of an artwork, which makes the artwork adapt to its specific environment and prolongs its working life (Gu et al., 2020). Nowadays, conventional coatings are used as a preservation technique of maintenance on public art. However, nanocoatings are a new technology to replace the traditional conventional coatings that are applied in the building and manufacturing industry. Koninklijke Oosterhof Holman is an integral infrastructure company that is interested whether nanocoatings can also be applied on reinforced concrete Dutch public artworks. Nanocoatings are coatings in which nanoparticles of a material are added. TiO_2 nanocoatings are already applied in the building industry and show improved characteristics over conventional coatings in terms of corrosion protection, water and ice protection, friction reduction, antifouling and antibacterial properties, heat and radiation resistance, and thermal management (Boostani and Modirrousta, 2016). Furthermore, nanoparticles in coatings can act as a photocatalyst in a photocatalyse reaction. Photocatalyse is a chemical reaction by means of a catalyst, which is accelerated by light. Photocatalyse on the surface of an artwork results in a self-cleaning effect and it improves the air quality.

In order to investigate the applicability of nanocoatings on reinforced concrete Dutch public art, an overview of nanocoatings and a conventional coating is created. The coatings are assessed on technical, economic and toxicity parameters.
The technical parameters needs to fulfill the purpose of increasing the durability of concrete with the efficacy of increasing the aesthetic view of art. Durability of concrete is defined as the ability to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties(McCarter et al., 2015). In order to asses this purpose, four technical parameters have been defined. Corrosion and wear are the two most common deterioration factors on reinforced concrete surfaces(Li, 2011), so corrosion and wear are two technical parameters in which the coatings are rated.

Another technical parameter on which is rated is adhesion. Poor adhesion of a coating on a surface causes blisters, bursts or cracks on the surface of the substrate or it even starts to peel-of(Møller and Nielsen, 2013), which is a counter-intuitive to the purpose of applying coatings on a surface. As last technical parameter, porosity is rated to decrease as water or harmful ions can penetrate more easily into porous materials, which causes internal chemical reactions that lead to cracks on the surface.

Since nanocoatings are new in the market, the purchase costs of nanocoatings are currently high compared to conventional coatings (Makhlouf and Tiginyanu, 2011). Furthermore, new nanocoatings require new application methods to apply a nanocoating on the surface (Makhlouf and Tiginyanu, 2011). Therefore, purchase cost and the price method of application are the two economic parameters.

At last, nanocoatings are mentioned to be the next asbestos or chrome-6 of coatings. As it is inevitable that nanoparticles end up into human, animal and plant cells (Aschberger et al., 2011), a cytotoxicity parameter is assigned. Cytotoxicity is the quality of being toxic to human, animal or plant cells. From this, the main research question is defined as:

Which nanocoatings score the highest rating on the defined technical, economic and toxicity parameters for application on reinforced concrete Dutch public artworks?

In this report, the technical, economic and toxicity parameters are rated based on a qualitative measuring system, in order to create an overview of suitable nanocoatings to apply on reinforced concrete Dutch public art.

2 Research outline: elements of interest to the limited available knowledge on the applicability of nanocoatings

In this chapter is explained why reinforced concrete Dutch public artworks have to be coated. Furthermore, a research goal and research questions are composed as a guidance to investigate the problem.

2.1 Problem analysis

Public art enriches the physical environments, by bringing buildings, schools and streetscapes to live. It covers topics from local history of a town (e.g. local heroes from the past), to nationwide subjects (Dutch history of slavery) to international issues (e.g. sustainability), which creates awareness and solidarity for inhabitants and tourists (van Burkom et al., n.d.). Furthermore, public art creates economic opportunities for artists to exhibit artworks and for local companies as restaurants, hotels and transportation companies, since an attractive site attracts visitors (van Burkom et al., n.d.).

However, maintenance is required to prevent deterioration on the surface of a public artwork. Deterioration of artworks involves cracks, color change and material loss on the surface (van Burkom et al., n.d.). Municipalities are responsible for the design of public space, architecture, interiors and exteriors, squares and bridges, and natural land as parks and landscapes (van Burkom et al., n.d.). Municipalities consider 3 measures to anticipate on this problem. Unfortunately, the first measure is doing nothing. Maintenance for all of their properties is expensive and time-consuming, which results in lacking of maintenance for public artworks. Nevertheless, public artworks are also cleaned or restored. However, cleaning or restoring is a short-term solution, cleaning and restoration cost are expensive and material properties are not improved, but only current damage is repaired (van Burkom et al., n.d.). Furthermore, restoration and washing keeps surface clean for approximately 5 years (Makhlouf and Tiginyanu, 2011). Since maintenance of all Dutch public art is time-consuming, long-term solutions are more favorable. Although applying conventional coatings on public artworks is also considered to be expensive, this offers a long-term solution (Gu et al., 2020).

Koninklijke Oosterhof Holman is an expert in infrastructural issues and is focused on environmental technology, concrete and hydraulic engineering, landscaping and plan development. Koninklijke Oosterhof Holman noticed deterioration of reinforced concrete Dutch public artworks and sees maintenance of reinforced concrete Dutch public art as a business opportunity to broaden their work field. Currently, Koninklijke Oosterhof Holman applies conventional coatings on concrete structures as roads, bridges and structures in hydraulic engineering, however Koninklijke Oosterhof Holman is aware of a new technology called nanocoatings. In literature, the function of nanocoatings show improved characteristics over conventional coatings in the building industry in terms of corrosion protection, water and ice protection, friction reduction, antifouling and antibacterial properties, self-cleaning, heat and radiation resistance, and thermal management (Boostani and Modirrousta, 2016). To start coating in a new segment in the market with a possible new coating technology, Koninklijke Oosterhof is interested in further investigation of applicable nanocoatings on Dutch public artworks.

2.2 Problem statement

Reinforced concrete Dutch public artworks deteriorate due to reducing material properties that are exposed to environmental influences and devastation by human influences. It is not known which nanocoatings fulfil the specified technical, financial and toxicity parameters.

2.3 Stakeholder Analysis

This research is commissioned by Oosterhof Holman. However, outdoor art is in possession of the government, in which local municipalities are involved(van Burkom et al., n.d.). In order to verify whether other parties are involved too, a stakeholder analysis is performed. The amount of power and interest of the stakeholders and the different goals of the stakeholders can affect the research and design proposal to scope more to a technical or a financial outcome of the research. The following stakeholders have been identified and are listed below according to power and interest:

- **Wijbrand Attema of Koninklijke Oosterhof Holman:** Wijbrand Attema is project manager at Koninklijke Oosterhof Holman, and is the client of this research. This integrated project is carried out on their behalf and the outcome of this research could be a start for further investigation on nanocoatings. In the end, it could broaden the work field for the company. This makes them the problem owner hence Mr. Attema has high power and a high interest.

- **Research institute ENTEG:** Research institute ENTEG has low interest, because the new technologies regarding nanocoatings is only a small part of their broad interest. ENTEG can only use the outcome of this integrated project for further research and are thus more interested in the technical aspect than the implementation aspect. Furthermore, they have low power, because they do not have an active contribution to this project.

- **Local municipalities:** Local municipalities have the authority to approve these projects to their local art. This gives them significant power and interest. Their interest is both focused on the financial and technical outcome of this research. As they will be the client for Koninklijke Oosterhof Holman to execute the preservation of public art, the quality of the nanocoating as well as the sustainable and the financial part are of importance.

- **Rijkswaterstaat:** Rijkswaterstaat is the executing agency of the Ministry of Infrastructure and Water Authority and provides data regarding concrete public art in the Netherlands. This gives them a significant amount of power, but low interest.

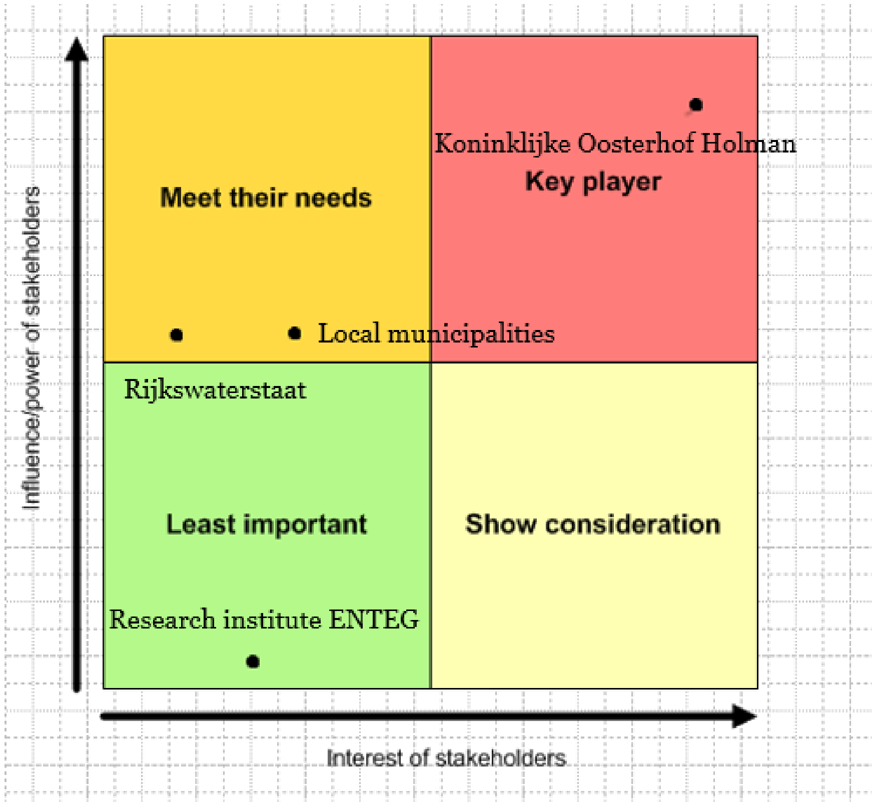

Figure 1: Stakeholder matrix for this research

2.4 Research Objective

To create an overview of suitable nanocoatings for the company Koninklijke Oosterhof Holman within 12 weeks that are rated on technical, financial and toxicity parameters to prevent deterioration of reinforced concrete public artworks in the Netherlands.

2.5 Research Questions

Which nanocoatings score the highest rating on the defined technical, economic and toxicity parameters for application on reinforced concrete Dutch public artworks?

1.1 Which structural components of concrete on nanoscale declare its material and mechanical properties?

1.2 Which nanocoatings increase the wear resistance of reinforced concrete Dutch public artworks?

1.3 Which nanocoatings increase the corrosion resistance of reinforced concrete Dutch public artworks?

1.4 Which nanocoatings have strong adhesion on a concrete surface?

1.5 Which nanocoatings result in a decrease of porosity?

1.6 Is it economically feasible for Koninklijke Oosterhof Holman to implement nanocoatings on reinforced concrete Dutch public art?

1.7 Is it toxic for human, animal and plant cells to apply nanocoatings on reinforced concrete Dutch public artworks?

1.8 To which weighting factor can the technical, financial and toxicity parameters be assigned to?

3 State-of-the-art: body of knowledge on concrete, conventional coatings and nanocoatings

In this chapter is discussed what is known in the literature on concrete structures on macroscale, microscale, and nanoscale. Furthermore, an introduction is provided on conventional coatings, nanocoatings, nanomaterials and additional advantages of nanoparticles.

3.1 Concrete composition

To find solutions for increasing the service life of a concrete artwork, first, the underlying causes of deterioration of concrete must be specified. Properties can be originated from its internal structure. To detect the degradation of properties on macroscale, the structure of concrete has to be analysed on microscale or even on nanoscale (Sanchez and Sobolev, 2010).

3.1.1 Concrete composition macroscale

Concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard matrix of material (the cement or binder) that fills the space among the aggregate particles and glues them together. Cement can be hydraulic or non-hydraulic (Li, 2011). Non-hydraulic cement is mainly used for materials with liquid properties, so to create public concrete art, hydraulic cement is used. Water is used to mix. This water reacts in hydraulic concrete, which strengthens the material. In this report, the term concrete refers to Portland cement concrete as it is the most common used cement in circulation. The composition of Portland cement concrete can be find in figure 2.

Portland cement
+ water (& admixtures) → cement **paste**
+ fine aggregate → **mortar**
+ coarse aggregate → **concrete**

Figure 2: Concrete composition

3.1.2 Concrete composition nanoscale

Concrete consists out of three different phases on nanoscale; aggregate particles, hydrated cement paste(HCP) and a transition zone. These three phases have in common that each particle may contain several materials, in addition to micro cracks and voids, just as they contain a heterogeneous distribution of different types and amounts of solid phases, pores and micro cracks (Li, 2011)(Böhni, 2005). Unlike other materials, these structures do not remain stable as the cement paste and transition zone are subject to change over time, environmental humidity and temperature (Li, 2011).

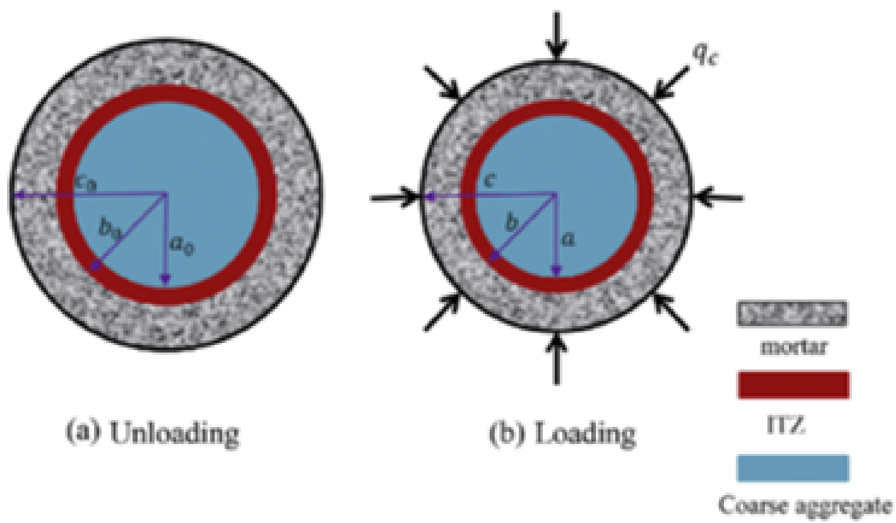

Figure 3: Profile of loaded and unloaded concrete on nanoscale

Course aggregate particles

The course aggregate particles are the materials that are added to the cement paste in order to obtain concrete. By adding aggregates, the material obtains strength, but this also has an undesirable side effect, which is the Alkali–aggregate reaction(AAR). The Alkali-aggregate reaction is a reaction that occurs between the alkalis in the pores of cement past and course aggregates. Alkali refers to the content of Na2O and K2O in cement paste. This reaction causes cracking and is fed by moisture conditions. Moisture conditions cause that water is present in the pores and on the surface of the aggregate.

Deterioration can be caused by internal implications as property degradation and external implications as loading and the environment. The Alkali-aggregate reaction can be considered as internal degradation of the material, but can be reduced by decreasing the permeability of concrete. The presence of Fe- and Al-rich coatings may influence the kinetics of the alkali–aggregate reaction (Li, 2011).

Hydrated cement paste

50 to 70 % of the hydrated cement paste phase consists of the calcium-silicate-hydrate structure (C-S-H). The C-S-H structure is considered to be responsible for the strength of concrete and is responsible for shrinkage cracks. Shrinkage is a decrease in either length or volume of concrete resulting from changes in moisture content or chemical changes in the hydrated cement paste caused by weather conditions. The shrinkage strain is time-dependant, so especially for public artworks, shrinkage cracks are a frequent deterioration factor. The most effective way of preventing shrinkage is by sheltering the surface from sunshine or wind. As this is not possible for Dutch concrete public artworks, coating can be applied on the surface to further prevent shrinking (Li, 2011).

Transition zone

Transition zone or interfacial zone represents the interfacial region between the aggregate particles and the C-S-H particles and are typically 10 to 50 µm thick. The transition zone is generally weaker than either of the two other phases of concrete. The volume fraction only represents a few percent, but it has definitely influence on concrete properties. Although the transition zone is composed of the same elements as the hydrated cement paste, the structure and properties of the transition zone are different from HCP. The transition zone is porous, which affects the entire material, as makes the material more permeable. The level of permeability of the material determines the amount of fluids that are able to enter or leave the pores. In conclusion, the permeability is one of the most important factors of deterioration of reinforced concrete public art as all different materials, ions and fluids can penetrate into the concrete, which in the end causes cracks and surface colouring. Permeability and porosity have a positive correlation (Li, 2011). Therefore, when the KPI of porosity set to decrease is obtained, the decrease of the permeability is set to decrease too.

3.1.3 Deterioration of reinforced concrete Dutch public art

Reinforced concrete Dutch public art is deteriorating due to 3 main factors: internal deterioration of the material, environmental influences or human devastation. Firstly, chemical reactions occur over time in concrete, which causes cracks on the surface. Secondly, environmental influences cause concrete to deteriorate. Dutch public art is open and exposed to the environment. The winters in the Netherlands are quite soft, but it has 50 frosty days per year. Variety of rain and frost causes cracks or corrosion to the artwork. Besides, deterioration is expected to increase since rainfall in the Netherlands is increasing over the years and more CO2 is included in raindrops (Li, 2011). More raindrops can penetrate into the material, which causes chemical reactions that cracks the material. At last, humans devastate public artworks via spraying graffiti, climbing on artworks or burning them.

3.2 Conventional coatings

Koninklijke Oosterhof Holman applies an epoxy resin coating on concrete surfaces as bridges to improve the aesthetics and to make the surface hydrophobic. Epoxy resins are widely-used polymeric materials and are applied in many different industries as the building industry, the automotive industry or in the electronics industry (Parimalam et al., 2018). The epoxy resin of Koninklijke Oosterhof Holman is transparent and is a strong barrier coating. A barrier coating forms an insulating and physical barrier to protect corrosive elements (Böhni, 2005). The epoxy resin is applied to the surface via spraying, rolling or via layer decomposition with a trowel. The epoxy resin coating lasts for 10 years on untreated surfaces as walls.

3.3 Nanocoatings

In this section, the characteristics of nanocoatings are elaborated. What are nanocoatings? And why are nanocoatings interesting to further investigate. The key mechanism is that nanocoatings can act as a photocatalyst, which results in the self-cleaning ability(Makhlouf and Scharnweber, 2015).

3.3.1 Basics of nanocoatings

A coating is a method to modify the surface properties of an artwork, which makes the artwork adapt to its specific environment and prolongs its working life (Gu et al., 2020). However, also nanoparticles can be added to a coating in order to make use of the specific properties of nanoparticles. For a particle to be a nanoparticle, at least one of its dimensions must be smaller than 100 nanometers. Although nanoparticles are relatively small, nanoparticles actually have a comparatively large surface area as when particles are broken down into smaller particles, the total surface area of the smaller particles increases. The increased surface area leads to a faster rate of surface-level reactions as photocatalysis (Gu et al., 2020).

3.3.2 Photocatalysis

Photocatalysis is a chemical reaction, which is accelerated by light and can be compared with photosynthesis(Figure 4). Light energy is converted into chemical energy, which is transferred to water vapour to produce active oxygen species at the surface (Makhlouf and Tiginyanu, 2011). The active oxygen species on the surface start simultaneously oxidation and reduction reactions with smog, pollutants and stain-causing substances and decomposes soiling into carbon dioxide and water. Furthermore, water is strongly attracted to the nanoparticles(Makhlouf and Tiginyanu, 2011). The attractive force causes a strong hydrophilic effect, which indicates that the nanocoating does not allow water to form droplets on the surface. Instead, it forms a sheet that undercuts the dirt, flushes it away and dries quickly. This is called the self-cleaning ability of nanocoatings. Photocatalysis helps the surface to remain clean and it improves the air quality (Goffredo and Munafò, 2015). Nanoparticles act as a photocatalyst on the surface and hence, a material that supports both oxidation reactions and reduction reactions is required (Tahir et al., 2020).

3.3.3 Semiconductors as a photocatalyst

Due to their electronic properties, only semiconductors can act as a photocatalyst. A semiconductor is a solid substance that has a conductivity between that of an insulator and that of most metals, has a moderate band gap and has capabilities of oxidation and reduction perform simultaneously (Tahir et al., 2020). However, still, not all semiconductors are suitable as photocatalyst. A semiconductor is suitable as a photocatalyst when it has a low recombination rate, and the absorption wavelength (350-700nm) and visible region or band gap(1.5-3.5 ev) should fall within limits. Moreover, for material to act as a photocatalyst, it should be chemically stable and have a high photocatalytic activity (Makhlouf and Tiginyanu, 2011).

3.3.4 Identification of nanocoatings

Nanomaterials can be subdivided into three categories: metals, polymers and ceramics (Makhlouf and Scharnweber, 2015). In order to determine which nanoparticles are considered to be most suitable to apply on concrete Dutch public art, the photocatalytic properties of these categories are considered. Generally, ceramics fulfill the requirements to act as a photocatalyst. Ceramics consist of metal (aluminum or titanium) and non-metal (oxides, nitride, or carbide) particles. Ceramics have a suitable light absorption, electronic structure, band gap and carrier transportation to act as a photocatalyst. Also, certain polymeric nanoparticles can act as a semiconductor. However, the success of photocatalysis of polymeric nanoparticles depends on the synthesis technique (Tahir et al., 2020). Polymers can be divided into organic and inorganic polymers. Organic polymers are materials that essentially contain carbon atoms in the backbone and inorganic polymers have a skeletal structure that does not include carbon atoms in their backbone. At last, metal nanoparticles are not suitable as a photocatalyst. Metal nanoparticles are conductors and there is no band gap between their valence and conduction bands (Tahir et al., 2020).

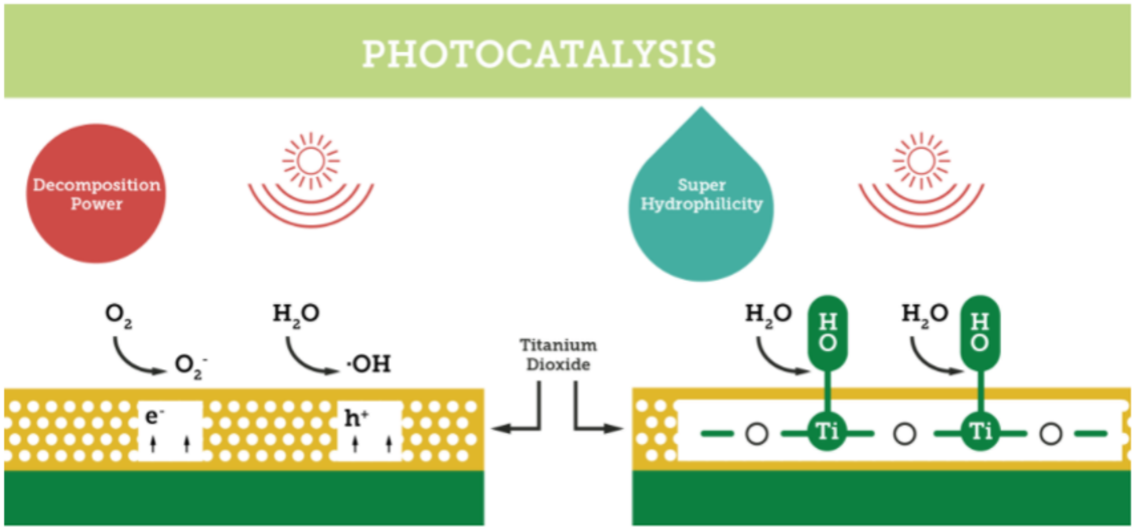

Figure 4: Photocatalysis

4 Methodical approach used for nanocoating comparison

In this chapter is the methodology of the nanocoating assessment explained. At first, parameters are depicted on which the nanocoatings are rated. After that is the qualitative rating system, the method of conducting literature research and the filtering method of the nanocoatings explained.

4.1 Key performance indicators

In this section, key performance indicators are defined that a coating needs to fulfill to increase the material properties of the reinforced concrete Dutch public artworks. Nevertheless, the nanocoatings should also be an interesting business opportunity for the problem owner to implement. Therefore, the KPI's are subdivided into three different parameters: technical parameters, financial parameters and toxicity parameters.

4.1.1 Technical parameters

In order to increase the material properties of reinforced concrete Dutch public art, the overview of nanocoatings are assessed on 4 wear resistance, corrosion resistance, adhesion and porosity.

Wear

The first technical parameter is defined as wear resistance. Wear on concrete Dutch public art is connected to a loss of material. Abrasive wear is the most common form of wear(Møller and Nielsen, 2013). Abrasive wear in this case is indicated as deterioration of the surface in connection with weather conditions as freeze-thrawing. The winters in the Netherlands are quite soft, but it has 50 frosty days per year. Destructive wear leads to surface mortar spalling, aggregate exposure and cracks on the surface(Li et al., 2021), which damages the view. Public artworks are, in some examples, exposed to abrasive wear for more than 80 years. Abrasive wear is after corrosion resistance the most important factor affecting durability of concrete artworks(Li et al., 2021). Furthermore, wear resistance of concrete mainly depends on the surface performance of the material. By coating a surface, wear resistance can improve significantly(Li et al., 2021), hence wear resistance is considered to be a relevant KPI.

Wear resistance can be improved by improving the hardness, the density and the interfacial bond strength on the surface of concrete. Mainly the hardness can be increased by adding a coating on a surface. Therefore, wear resistance testing is focused on increasing the hardness of the surface. Many different tests are applied to quantify hardness of the surface, such as the scratch resistance test, the pin-on-disk test or the abrasion test(Sepeur et al., 1999) (Barna et al., 2005). The focus in searching for literature on wear-resistance of coatings is on concrete surfaces. However, by unavailability of literature, wear-resistance can also be measured after a nanocoating is applied on a different substrate than concrete. The resistance of wear is defined as high, medium, low or not. High wear-resistance indicates that application of the coating indicates a low material loss of a hardness test on the coated specimen and a low wear-resistance indicates a high material loss of a hardness test on the coated specimen.

Adhesion

Adhesion is the state in which two surfaces have been bonded by a chemical or physical force or a combination of both via an adhesive medium(Møller and Nielsen, 2013). Poor adhesion results in blisters, bursts, or cracks on the surface of the substrate or it even starts to peel of, which is counter-intuitive to the purpose of applying coatings on a surface(Ali et al., 2021). Therefore, adhesion is considered as a technical requirement on which the nanocoating is rated. The adhesion of the coating on concrete is tested via microstructural analysis in literature (Møller and Nielsen, 2013). After coating the concrete surface, cracks can be visualised on microscale. Since adhesion is specific for a nanocoating and concrete, adhesion cannot be tested on surfaces other than a concrete surface(Ali et al., 2021). To conclude, based on the results of a specific test in the literature, adhesion of the coating to the surface is defined as high, medium, low or not. Low adhesion indicates that application of the coating on the surface results in cracks on the surface on microscale. On macroscale does this result in cracks on the surface of concrete. High adhesion indicates that no cracks appear on microscale and macroscale.

Corrosion

Plain concrete does not easily withstand forces from humans or wind executed on the surface. Therefore, reinforced concrete is often applied in Dutch public art instead of plain concrete in order to sustain the tensile strength of concrete with steel bars. However, corrosion is responsible for up to 90 % of damage to reinforced concrete structures(Böhni, 2005). The two most common mechanisms of reinforcement corrosion are caused by penetration of CO_2 or chloride-ion into the concrete and react with steel. Rainwater, seawater or deicing salts contain chloride ions. These chloride ions can reach the surface of the steel bar through the porous concrete. The corrosion process initiates when the chloride ions break a certain threshold level at the steel surface, which can be defined as the content of chloride at the steel depth that is necessary to sustain local film breakdown(Zafeiropoulou et al., 2013). Furthermore, most concretes have a pH of 12.5-13.8 (Taheri, 2019). However, the pH can be lowered due to carbonation. Carbonation of concrete is a process by which carbon dioxide from the air penetrates into the concrete through pores and reacts with calcium hydroxide to form calcium carbonates1(Safiuddin et al., 2014). In the presence of moisture, CO2 changes into dilute carbonic acid, which attacks the concrete and reduces the pH value of concrete to approximately 9. This pH value is leading to a general breakdown in passivity and as a result, rebars are starting to corrode(Zafeiropoulou et al., 2013). This means that electrochemical oxidation of metal in reaction with an oxidant such as oxygen or sulfates starts. By coating reinforced concrete, the electrical resistivity on the surface changes, which reduces the corrosion activity(McCarter et al., 2015).

Corroding causes internal cracks that make their way to the surrounding concrete and damages the surface. These corrosion cracks cause that even more CO2 and chloride ions penetrate into the concrete, which makes the cracks even worse. The corrosion rate can be tested via field testing or via laboratory testing(Møller and Nielsen, 2013). Field testing involves exposure of components of the surface into corrosive environments, such as seawater of coast near regions. The field test should contain UV exposure from solar radiation, temperature variation and humidity or moisture variations(Møller and Nielsen, 2013). Field testing is the most reliable test method to determine the corrosion resistance and durability of the coating. However, the downside is that it is a time-consuming process and can take up to several years(Møller and Nielsen, 2013). As nanocoatings are such a new technology and not many literature is available on field testing of new nanocoatings, this research focuses on laboratory testing. Within laboratory testing on corrosion resistance, bars are exposed to a corrosive environment, while material loss or electric measurements are conducted over time. The focus in searching for literature on corrosion-resistance of coatings is on reinforced concrete surfaces. However, by the unavailability of literature, corrosion resistance can also be measured on surfaces of other materials. Corrosion resistance is defined as high, medium, low or not. High corrosion resistance indicates no influence of the corrosive environment on the coated specimen and low corrosion resistance indicates a strong influence of the corrosive environment on the coated specimen.

$$Ca(OH)^2 + CO_2 ==> CaCO_3 + H_2O. \tag{1}$$

Porosity
To reduce the permeability of concrete, the porosity of concrete must be decreased. Porosity measures the percentage of pore space occupies on the surface and concrete is characterized as a porous material. A more porous material is less well protected against weather conditions since precipitations penetrate more deeply into the material(Graziani et al., 2016). Furthermore, reducing the porosity results in higher resistance to the penetration of deleterious agents as for example, graffiti, CO_2 or water(Safiuddin et al., 2014). The graffiti penetrates less deeply into the material and it becomes easier to remove the graffiti by cleaning. Examples of testing on porosity is a water displacement test or analyzing the microstructure of the coated concrete(Ali et al., 2021). Porosity is defined as high, medium and low, in which high porosity of the coated specimen is qualified as unsuitable and a low porosity is qualified as suitable for the application.

Not included parameter
The increase of the strength of the nanocoating on concrete is not considered in this system. Reinforced concrete is mainly applied in the construction industry, in which strengths of multiple orders of magnitudes are applied on, compared to reinforced concrete public art(Munafò et al., 2015). Therefore, increasing the strength of the surface of reinforced concrete Dutch public art has little influence on preventing the deterioration of reinforced concrete Dutch public art.

4.1.2 Financial parameter

The purchase price and the cost method of application are considered to assess which nanocoatings are financially interesting for further investigation

Purchase cost
Since nanocoatings are new in the market, the purchase costs of nanocoatings are currently high compared to conventional coatings(Gu et al., 2020). Certain nanocoatings are not even produced on a big scale yet, making them less interesting for Koninklijke Oosterhof Holman to further investigate. However, an indication of possible future purchasing costs can be investigated in order to filter nanocoatings that are too costly. To assess the purchase price, an estimation is indicated via rating the purchase costs from 0-3. 0 indicates a high purchase cost and 3 indicates a low purchase cost.

Price method of application

There are many different coating technologies(Electro- and electroless chemical plating, conversion coating, Chemical and physical vapor deposition, Spray coating, Sol–gel coatings). The price of applying coatings on a surface differs per coating technology. Not all nanocoatings can be assigned to all coating technologies. Certain nanocoatings can only be applied on a surface via a specific coating technology(Makhlouf and Tiginyanu, 2011), of which it is expected that it is expensive related to the other coating technologies. Therefore, an estimation of the price method of application is indicated via rating the price method of application from 0-3 in which 0 indicates high price method of application and 3 indicates the low price method of application.

4.1.3 Toxicity parameters

The last factor to determine is the cytotoxicity parameter. Cytotoxicity is the quality of being toxic to human, animal or plant cells. Since nanocoatings are such a new technology, the toxicity of nanoparticles remains a controversial subject. Nanocoatings are mentioned to be the next asbestos or chrome-6 of coatings(Pacheco-Torgal et al., 2012). When the total application of nanocoatings increases, the amount of nanoparticles that arrive into the environment and end up in human, animal or plant cells also increases.

Humans are exposed to the inhalation of nanoparticles during the manufacturing process when raw nanomaterials are handled in large quantities. Therefore, nanoparticles are going to arrive in human cells. Furthermore, it is inevitable that nanoparticles of nanocoatings are going to arrive in soils, sediments and wastewater when nanocoatings are applied on a big scale since micro parts of coatings crumble and derive into the environment(Aschberger et al., 2011).

From bulk materials cannot be determined whether its nanoparticle is toxic. It is already known that the toxicity of nanoparticles depends on several factors such as chemical composition, crystalline structure, size, and aggregation(Soto et al., 2007). Although chrysotile asbestos has been demonstrated to be morphologically identical to many forms of carbon nanotubes and its short-term cytotoxic response for animal plant cells has been demonstrated to be identical to multi-wall carbon nanotubes, there is no evidence yet that nanoparticles can cause equal long term hazard as asbestos(Soto et al., 2007). However, short-term responses should be regarded as a warning for further investigation.

The dimensions of nanoparticles are similar to those of viruses and some small bacteria and have the ability to affect cellular processes and cause disease(Pacheco-Torgal et al., 2012). Inhaled nanoparticles can enter the circulatory blood system and has been shown to reach organs translocating from lungs to blood, liver, kidneys, spleen, brain and heart(Pacheco-Torgal et al., 2012). Depending on the cytotoxicity, nanoparticles can cause circulatory diseases, various cancers, heart diseases and brain diseases. The environment is exposed to risk when nanoparticles arrive into algae. The arrival of cytotoxic nanoparticles in algae results in growth reduction(Wei et al., 2010). Algae are the source of more than half of the world's oxygen through photosynthesis and are the base of the food chain. Therefore, the decreased growth of algae could disrupt the entire food chain. The rating of this parameter is determined by a comparison of the cytotoxicity of the selected nanocoatings. Unfortunately, the information on consumer and environmental exposure of humans is too scarce to attempt a quantitative risk characterisation(Aschberger et al., 2011). Therefore, the cytotoxicity is rated from 0-3 in which 0 indicates high toxicity and 3 indicates no toxicity.

4.2 Qualitative rating matrix and analytical hierarchical research

This section explains the qualitative rating matrix in which the epoxy coating, the nanocoatings are rated on the depicted parameters. The analytical hierarchical process is going to determine the weighting factor of the parameters in the qualitative rating matrix.

Qualitative rating matrix

The depicted nanocoatings are rated for every distinct parameter in a rating matrix from 0-3, in which 0 is qualified as not suitable and 3 is qualified as highly suitable. A qualified rating system is chosen over a quantified rating system as many different testing methods are applied to rate the effectiveness of a coating on the improvement of material properties. By combining the information of several pieces of research, a qualified rating of the nanocoatings relative to each other can be given. Furthermore, parameters of nanocoatings on which no literature can be found are rated with a question mark. In the calculations, the question marks are considered to be 0.

Analytical hierarchical process table

In order to determine the importance of the KPI's relative to each other, an analytical hierarchical process table is composed and sent to three experts in the area of concrete coatings of Koninklijke Oosterhof Holman. Based on the research goal of finding the most suitable nanocoating for reinforced concrete Dutch public artworks, the experts rated the 7 parameters relative to each other. With the results, a weighing factor from 0-1 per parameter is obtained. By multiplying the rating of the parameter of a nanocoating, the total suitability score becomes more accurate.

4.3 Information gathering

The information sources are searched via SmartCat, Google Scholar and Web of Sciences in the form of articles, papers, books and journals. Literature research is focused on finding studies in which multiple nanocoatings are investigated on multiple parameters to prevent that more different methods of testing were applied. This delivers more accurate qualitative ratings. Furthermore, interviews with employees of Koninklijke Oosterhof Holman are conducted in order to make use of their knowledge regarding coating, maintenance and concrete, and to ensure to remain the same focus and interest.

4.4 Nanocoating filtering

Due to the self-cleaning advantages of photocatalysis, which reduces cleaning costs and improves the aesthetics of concrete art, the nanocoatings are filtered on photocatalytic properties. Therefore, metal nanocoatings are not considered in this research. Also, organic nanocoatings are not considered. Although organic coatings can be produced that contain photocatalytic activity, the synthetic techniques are complicated and costly to obtain photocatalytic properties(Tahir et al., 2020). Furthermore, organic polymeric coatings are permeable to corrosive species such as oxygen, water, and chloride ions(Makhlouf and Scharnweber, 2015). Due to time limitations and availability in literature, only metal-oxides are considered of the ceramics. The metal-oxides and inorganic polymers are depicted based on availability in literature research. Availability in literature research indicates that implementation of the nanocoatings is closer to big-scale production and thus more interesting for Koninklijke Oosterhof Holman.

5 Resulting overview using the methodological approach

This chapter provides the ratings of the nanocoatings and the epoxy coating on technical, financial and toxicity parameters. The choice of rating is explained for all parameters per coating. In the last section can the qualified rating matrix be found.

5.1 Technical parameter rating

This section is divided into subsections per additional research. In the investigations, laboratory tests are performed to assess wear resistance, corrosion resistance, adhesion and porosity of nanocoatings. According to the qualified rating system, a rating is given.

5.1.1 Wear resistance, adhesion and porosity of TiO_2, MgO, ZnO and ZrO_2

Concrete samples were coated with TiO_2, MgO, ZnO and ZrO_2 nanocoatings with different weight percentages and tested on wear resistance, adhesion and porosity(Ali et al., 2021). An average of the different weight percentages have been used in the results and can be found in Table 1.

A SEM analysis was conducted to view the mineralogy that lies inside the composite structure. The SEM analysis showed that in TiO_2, MgO and ZrO_2 coated substrates, no cracks appear in the transition zone, which indicates strong adhesion. ZnO-coated surfaces showed small cracks in the transition zone, which indicates weaker adhesion.

Table 1: Research 1

	TiO_2	MgO	ZnO	ZrO_2	Uncoated
Abrasion test					
Abrasion rate (g/min)	32	33	37	28	43
Wear-resistance rating	2	2	1	3	
SEM-analysis					
Adhesion rating	3	3	1	3	
Water displacement method					
Porosity(%)	2.6	2.25	2.6	2.75	3.5
Porosity rating	3	2	3	2	

5.1.2 Adhesion and porosity of TiO_2, SiO_2 and Al_2O_3

Concrete samples were coated with TiO_2, SiO_2 and Al_2O_3 nanocoatings and tested on adhesion and porosity via microstructure analysis (Muñoz et al., 2010). The microstructure analysis shows the volume distribution of pores in the transition zone of samples coated with nanoporous films. The TiO_2, SiO_2 and Al_2O_3 coated surfaces show a relative porosity percentage of 12%, 8% and 7% respectively. As TiO_2 is already rated 2 on porosity and SiO_2 and Al_2O_3 both score significantly better than TiO_2, SiO_2 and Al_2O_3 are both rated 3 on porosity.

The microstructure analysis shows no indications of bad adhesion on all three nanocoatings. As TiO_2 is already rated with a 3 on adhesion, both SiO_2 and Al_2O_3 are also rated with a 3 on adhesion.

5.1.3 Wear resistance of TiO_2, SiO_2, Al_2O_3 and Fe_2O_3

Organic polymer samples were coated with TiO_2, SiO_2, Al_2O_3 and Fe_2O_3 nanocoatings and tested on wear resistance via a scratch resistance test(Sepeur et al., 1999). A diamond indenter was pulled over the coating, which causes scratch marks in the coating. These scratches are measured under the microscope. The research does not show exact results, but according to the microscope results, the penetration depth of TiO_2, SiO_2 and Al_2O_3 are roughly equal and the penetration depth of Fe_2O_3 is twice as deep as the other nanocoatings. TiO_2 is already rated with a 2 on wear resistance and since SiO_2 and Al_2O_3 show equal wear resistance, they are also both rated with a 2 on wear resistance. Because Fe_2O_3 shows a doubled penetration depth in the scratch resistance test, Fe_2O_3 is rated with a 0 on wear resistance.

5.1.4 Wear and corrosion resistance of Fe_2O_3, ZnO and NiO

Steel bars were coated with TiO_2-Fe_2O_3, TiO_2-ZnO and TiO_2-NiO nanocoatings and tested on wear and corrosion resistance(Benitha et al., 2017). As Fe_2O_3, ZnO and NiO are all tested with an equal TiO_2 weight percentage, mutual relations between these nanocoatings can be rated.

Wear resistance is tested via high energy ball milling and measuring the material weight loss. The weight loss results of Fe_2O_3, ZnO and NiO in mg are 6.56, 2.4 and 8.43, respectively. Following the arguments in section 5.1.1, ZnO is rated with a 1 on wear resistance. Because both Fe_2O_3 and NiO perform worse on wear resistance, Fe_2O_3 and Nio are both rated with a 0.

Corrosion resistance is tested by exposing the coated steel bars to a corrosive solution and measuring the corrosion protection via potentiodynamic polarization measurements and wet corrosion techniques. The results of Fe_2O_3, ZnO and NiO show corrosion protection of 98.18%, 99.19 and 86.15%, respectively. Therefore, Fe_2O_3 and ZnO are rated 3 and NiO is rated 2 on corrosion resistance.

5.1.5 Adhesion of Fe_2O_3 and NiO

On the adhesion of Fe_2O_3 and NiO on concrete is no literature found. Hence this box is filled with a question mark in the rating matrix.

5.1.6 Porosity of SiO_2, Fe_2O_3 and NiO

SiO_2, Fe_2O_3 and NiO particles are added to Ordinary Portland Cement to improve material properties at the production of concrete(Zhang et al., 2019). According to Mercury intrusion porosimetry (MIP) tests, the porosity of the concrete is measured. The results of the ordinary concrete, SiO_2 concrete, Fe_2O_3 concrete and NiO concrete show a porosity of 35.01%, 23.69%, 25.56% and 14.96% respectively. Therefore, Fe_2O_3 is rated 2 and NiO is rated 3 on porosity.

5.1.7 Corrosion resistance of SiO_2 and ZnO

Steel bars were coated with SiO_2 and ZnO nanocoatings and tested on corrosion resistance(JOHARI et al., n.d.) via a salt spray test. After exposing the coated steel bars to a salt spray test, the thickness of the coatings has been measured via a UV test. SiO_2 and ZnO showed similar results in thickness after exposure to the salt spray test. Therefore, SiO_2 is equally rated as ZnO with a 3 on corrosion resistance.

5.1.8 Corrosion resistance of TiO_2

An aluminium bar was coated with a TiO_2 nanocoating and tested on corrosion resistance by exposing the aluminium bar to a corrosive solution(He et al., 2013). Via potentiodynamic polarization measurements, the coating has shifted corrosion potential from -0.865 Volt to 0.656 Volt. The greater the corrosion potential is, the less tendency of the metallic element to be oxidized or dissolved. Thus, the decrease of corrosion potential indicates the improvement of corrosion resistance by the coated aluminium bar. Also in books as (Makhlouf and Tiginyanu, 2011) and (Hosseini and Karapanagiotis, 2018), nanocoatings containing TiO_2 are stated to be highly suitable to apply as a corrosion-resistant coating. Therefore, TiO_2 is rated 3 on corrosion resistance.

5.1.9 Corrosion resistance of ZrO_2

Brass surfaces were coated with ZrO_2 nanocoatings(10nm, 35 nm and 100nm thickness) and tested on corrosion resistance by exposing the brass surface to a corrosive solution(Holgado et al., 2002). The corrosion–protective effect of the coating is measured via a voltagram to detect current on the surface of the brass specimen. A high current indicates more corrosive activity. Hence a low measured current is favorable for corrosion resistance. The results show that for the 100nm coating, practically no current could be detected in the voltagram. However, 10nm coated brass specimens show approximately 50 μ A, compared to a current of 125 μ A of the uncoated brass specimen. Therefore, ZrO_2 offers corrosion resistance, but a significant coating thickness is required to withstand corrosion. Therefore, ZrO_2 is rated with a 2.

5.1.10 Corrosion resistance of Al_2O_3 and TiO_2

Aluminium bars were coated with Al_2O_3 and Al_2O_3-TiO_2 nanocoatings and tested on corrosion resistance by exposing the aluminium bars to a corrosive solution and measuring the weight loss over time(Herrmann et al., 2014). The results show that the addition of TiO_2 to the Al_2O_3 nanocoating decreases the weight loss of the coated bars in corrosive environments of approximately 20%. Comparing these results with the research of (Benitha et al., 2017) in which weight loss percentage are more widespread, Al_2O_3 is still rated with a 2.

5.1.11 Corrosion resistance of MgO and TiO_2

Lithium-rich cathode material bars were coated with MgO and TiO_2 nanocoatings and tested on corrosion resistance via exposing the coated Lithium-rich cathode material bars to a corrosive solution and measuring the current via a voltagram(Xiao et al., 2019). The results show a voltage of 147.56 and 137.96 mAh $g^{-}1$ respectively. Therefore, the performance of the TiO_2 nanocoating offers better corrosion resistance than the MgO nanocoating. However, the article states that both nanocoatings play a significant role in strengthening the electrochemical performance of Li-rich cathode materials. Therefore, the Mgo nanocoating is rated 2.

5.1.12 Adhesion and porosity of graphene

Concrete samples were coated with TiO_2-graphene nanocoatings, compared with uncoated concrete samples and tested on adhesion and porosity via microstructural analysis(Guo et al., 2021). The chloride diffusion coefficient of the coated concrete samples compared with the uncoated concrete samples showed a decrease by 77.43 %, respectively. Hence, nanocoatings incorporating graphene in a nanocoating have a positive effect on decreasing porosity. Therefore, graphene is rated with a 3 on porosity.

Microstructural analysis of the coated concrete samples on adhesion shows small cracks in the transition zone. Furthermore, graphene is known to have poor adhesion properties and therefore, the addition of interfacial bonding strengths are required for improved adhesion(Guo et al., 2021)(Makhlouf and Scharnweber, 2015). Therefore, graphene is rated 1 on adhesion.

5.1.13 Wear and corrosion resistance of graphene

Aluminium bars were coated with a graphene nanocoating and tested on wear and corrosion resistance(Maeztu et al., 2017). Wear resistance is tested via a scratch test. The results show an increase in hardness of 125%. Because of this big increase, graphene is rated 3 on wear resistance.

Corrosion resistance is tested by exposing the aluminium bars to a corrosive solution and measuring resistance via electrochemical impedance spectroscopy. The results show a decrease of resistance over time from 24h 21.06 Ωcm2 to 168h 2.26 Ωcm2. A decrease in resistance indicates an increase in corrosion resistance. Furthermore, graphene is well-known for its corrosive properties (Makhlouf and Scharnweber, 2015). Therefore, graphene is rated 3 on corrosion resistance.

5.1.14 Wear and corrosion resistance, adhesion and porosity of epoxy resin

Reinforced concrete bars are coated with epoxy and epoxy-TiO_2 coatings, exposed to a corrosive environment and tested on corrosion resistance(Ramganesh et al., 2020). After exposure of 35 days, the results for the epoxy and epoxy-TiO_2 coated bars show a corrosion rate of 1.0628 and 0.6100 mills per year, respectively. As Al_2O_3 shows 20% more weight loss compared to TiO_2 and are rated with a 2, Epoxy is rated with a 1 on corrosion resistance.

Aluminium substrates are coated with epoxy, epoxy-TiO_2 and epoxy-ZnO coatings and tested on adhesion and porosity(Parimalam et al., 2018). Adhesion is tested via the cross-cut tape test. In this test, the percentage area where flacking or detached (coating removal) occur due to removal of an adhesive tape is measured. The results of the epoxy, epoxy-TiO_2 and epoxy-ZnO coatings show 5-15%, 0% and <5% coating detached. Following the rating of section 5.1.1, ZnO is already rated with a 1 on adhesion. Therefore, epoxy is rated with a 0 on adhesion.

The epoxy resin, epoxy-TiO_2 and epoxy-ZnO coatings are also investigated under the microscope. The results show that both epoxy-TiO_2 and ZnO coatings decreased the brittle properties of the aluminium substrates. The epoxy coating also decreased the brittle properties of the aluminium substrate, but less than the epoxy-TiO_2 and epoxy-ZnO coatings. As TiO_2 and ZnO are rated with a 2 on porosity, epoxy resin is rated with a 1 on porosity.

Furthermore, an aluminium bar is coated with an epoxy resin and an epoxy-TiO_2-SiO_2 coating and is tested on wear resistance via a dry sliding wear test(Lu et al., 2005). The results of the epoxy resin and the epoxy-TiO_2-SiO_2 coated bar show a weight loss of 52% and 30%, respectively. As TiO_2 and SiO_2 are both rated with a 2 on wear-resistance, epoxy is rated with a 1 on wear-resistance.

5.1.15 Wear and corrosion resistance and porosity of carbon nanotube

An aluminium alloy is coated with an epoxy resin and a Carbon Nanotube nanocoating and tested on wear and corrosion resistance and porosity(Khun et al., 2014). Wear resistance is tested via a ball-on-disk micro-tribological test. The results of the ball-on-disk micro-tribological test on the coated aluminium alloys with the epoxy resin and the Carbon Nanotube nanocoating show a penetration depth of 8.3 m and 0 m, respectively. As no wear is detected on the carbon nanotube nanocoating, the carbon nanotube nanocoating is rated with a 3 on wear resistance.

The aluminium alloy is exposed to a corrosive environment to test the corrosion resistance. The results show that the corrosion resistance in Ωcm2 of the epoxy resin coating is 15% higher than the Carbon Nanotube nanocoating. Following the rating of section 5.1.14, epoxy resin is already rated with a 1 on corrosion resistance. Therefore, the carbon nanotube coating is rated 2 on corrosion resistance.

Furthermore, the coated aluminium alloys are investigated under the microscope in order to test the porosity. The results show that the carbon nanotube nanocoating decreases the porosity in comparison to epoxy-coated alloy. Therefore, the Carbon Nanotube nanocoating is rated with a 2 on porosity.

5.1.16 Adhesion of carbon nanotube

A concrete surface is coated with a carbon nanotube coating and test on adhesion under the microscope(Irshidat and Al-Saleh, 2016). The results show that no cracks were visible in the transition zone of the coated concrete. Therefore, the carbon nanotube coating is rated with a 3 on adhesion.

5.2 Financial parameter rating

Currently, only TiO_2 and SiO_2 nanocoatings are available in the construction industry to apply on a concrete surface. However, the price of TiO_2 nanocoatings is intellectual property and only available for major customers. Therefore, the purchase price could not be obtained. SiO_2 nanocoatings that are currently available are focused on coating garden features and serves as a cleaning purpose. The quality of the coating is not sufficient for improving the material properties of reinforced concrete Dutch public artworks. In order to make an accurate purchase price comparison, the price of nanopowders is compared to rate the nanocoatings. Furthermore, the price method of application is left out of scope due to lack of information and lack availability of nanocoatings for concrete application. Therefore, the weighting factor of the purchase cost and the cost method of application is combined as a total cost weighting factor. Table 2 displays the price of nanopowder per gram and the assigned rating(*Sigma Aldrich Nanopowders*, n.d.). Since the purchase costs of epoxy is currently higher than the purchase cost of nanocoatings (Gu et al., 2020), the epoxy coating is rated with a 3 on the purchase cost.

Table 2: Price per nanopowder

	Price (€/g)	Rating
TiO_2	1,67	2
SiO_2	2,26	2
MgO	22,4	0
ZnO	1,8	2
ZrO_2	4,96	1
Al_2O_3	1,792	2
Fe_2O_3	1,58	2
NiO	1,93	2
Graphene	132	0
Carbon nanotubes	33	0

5.3 Cytotoxicity parameter rating

In this section, the cytotoxicity of the nanoparticles is determined based on laboratory tests.

5.3.1 Cytotoxicity of TiO_2, Fe_2O_3, Al_2O_3, ZrO_2, graphene and CNT

TiO_2, Fe_2O_3, Al_2O_3, ZrO_2, graphene and CNT nanoparticles have been characterized by transmission electron microscopy and assessed on cytotoxicity(Soto et al., 2005). Comparative cytotoxicological assessment of these nanomaterials was performed utilizing a murine (lung) macrophage cell line. Considering chrysotile asbestos to be a positive control, and assigning it a relative cytotoxicity index of unity 1.0, relative cytotoxicity indexes were observed: 0.4 for TiO_2, 0.7–0.9 for the Fe_2O_3, Al_2O_3 and ZrO_2 nanoparticles and 0.9 to 1.1 for the carbon nanotube nanoparticles and graphene. As a comparable cytotoxicity value as asbestos is not suitable for application, carbon nanotube nanoparticles and graphene nanoparticles are rated with a 0 on cytotoxicity. Fe_2O_3, Al_2O_3 and ZrO_2 are rated 1 on cytotoxicity and TiO_2 is rated 2 on cytotoxicity.

5.3.2 Cytotoxicity of TiO_2, SiO_2, ZnO and MgO

TiO_2, SiO_2, ZnO and MgO nanoparticles are added in vitro to a human small intestinal epithelium cell and tested on cytotoxicity (Gerloff et al., 2009). Cytotoxicity was determined by the lactate dehydrogenase (LDH) assay as a marker of cell membrane integrity with the leakage of LDH over time as a marker of cell membrane integrity. Membrane integrity is defined as the quality or state of the complete membrane in perfect condition. Release of LDH over time indicates a decrease in cell membrane integrity, which is an indication of toxicity. Taking the average of 20 g/cm2 and 80 g/cm2 concentrations after 24h, TiO_2, SiO_2, ZnO and MgO nanoparticles show 20%, 52%, 38% and 0% release respectively. Because TiO_2 is already rated with a 2 on cytotoxicity, MgO is rated with a 3, ZnO is rated with a 1 and SiO_2 is rated with a 0.

5.3.3 Cytotoxicity of TiO_2 and NiO

TiO_2 and NiO nanoparticles are added to cysteine and citrate solutions and is tested on cytotoxicity (Hahn et al., 2012). Cysteine and citrate solutions are natural components occurring in blood and therefore absorb the released nanoparticles. This imitates an in vivo research of nanoparticles arriving into human cells. According to a microscope analysis, the influence of TiO_2 and NiO nanoparticles on the cell viability show a 25% and 50% vitality reduction, which indicates a doubled cytotoxicity of NiO compared to TiO_2 nanoparticles. Therefore, NiO is rated with a 0 on cytotoxicity.

5.3.4 Cytotoxicity of epoxy resin

Epoxy resins do not contain nanoparticles or other toxic particles that are harmful when it arrives in human, animal or plant cells (Parimalam et al., 2018). Therefore, the epoxy resin coating is rated with a 3 on cytotoxicity.

5.4 Overview of results placed in the rating matrix

This section contains all the qulitaitive data defined in this chapter. The results are presented in table 3.

Table 3: Rating matrix nanocoating results

Coating type	**Wear**	**Adhesion**	**Corrosion**	**Porosity**	**Costs**	**Cytotoxicity**	**Total score**	**Weighted sum**
Weighting factor	0,16039	0,20925	0,1414	0,11716	0,09915	0,27265	1	
Conventional coating								
Epoxy Coating	1	0	1	1	3	3	9	1,53
Metal-oxides								
TiO_2	2	3	3	2	2	2	14	2,35
SiO_2	2	3	3	3	2	0	13	1,92
MgO	2	3	2	3	0	3	13	2,4
ZnO	1	1	3	2	2	1	10	1,5
ZrO_2	3	3	2	2	1	1	12	2
Al_2O_3	2	3	2	3	2	0	12	1,78
Fe_2O_3	0	?*	3	2	2	1	8	1,13
NiO	0	?*	2	3	2	0	7	0,83
Carbon-based materials								
Graphene	3	1	3	3	0	0	10	1,47
Carbon nanotubes	3	3	2	2	0	0	10	1,62

*Question marks are considered to be 0 in the calculations of the weighted sum

Table 4: Qualitative suitability matrix

0	Not suitable
1	Low suitable
2	Medium suitable
3	Highly suitable

From table 3 it is possible to derive that compared to the conventional coating (Epoxy Coating) not all nanocoatings have better scores based on the defined parameters. From the nanocoatings only TiO_2, SiO_2, MgO, Al_2O_3 and Carbon nanotubes are above the 1.53 threshold. The highest weighted sum, therefore likely the most attractive nanocoating to research further, is that of MgO with a score of 2.4. The coating with the worst score is that of NiO. Therefore, NiO should not be pursued in terms of further research if this rating matrix is considered. It also seen that Metal-oxides nanocoatings have higher weighted sums than carbon-based.

6 Discussion: implications of the resulting overview

This chapter discusses the results of the qualified rating matrix. Furthermore, future research steps for Koninklijke Oosterhof Holman and the University of Groningen are considered derived from this research's limitations.

6.1 Interpretation of results

Based on table 3 all nanocoatings score better than the epoxy coating on technical parameters. Therefore, according to this research, nanocoatings should be applied to reinforced concrete Dutch public artworks to increase the aesthetic view instead of an epoxy coating. However, only the epoxy coating scores suitability highly on both purchase costs and cytotoxicity. As exact purchase costs of nanocoatings are not determined, it is too early to state that nanocoatings are suitable for application on reinforced concrete Dutch public. Furthermore, it is inevitable that nanoparticles are going to end up in human, animal and plant cells(Pacheco-Torgal et al., 2012). As long as the long term effects of the cytotoxicity of nanoparticle is not yet clear, Koninklijke Oosterhof Holman can not take risks to apply nanocoatings.

6.2 Limitations and future research

This research serves as an initial starting point to determine whether Koninklijke Oosterhof Holman can implement nanocoatings on reinforced concrete Dutch public artworks. The qualitative rating method is not finite as it contains limitations on rating the nanocoatings on the technical, financial and toxicity parameters. Also, the filtering of nanocoatings and the final overview has limitations on which is elaborated in this section.

6.2.1 Qualitative rating method

The qualitative rating method is based upon scoring from 0-3. Since this margin is small, parameters of nanocoatings that scored slightly different results are still scored with the same number. Furthermore, considerable differences in results also have limited influence on the final weighted score. For example, the price of graphene nanopowder is 83.5 times higher than Fe_2O_3 nanopowder, but the weighted sum of graphene is still higher. In practice, the consequences of particular price differences would have more impact on a total suitability score. Increasing the scoring range could prevent this. Another factor that limited the qualitative rating method is the lack of available industrial research on nanocoatings. Since nanocoatings are such a new technology and there are not many researches available on practical applications of nanocoatings on concrete, all the research results are based on laboratory tests. Moreover, in literature are often combinations of different nanoparticles applied in a nanocoating(Benitha et al., 2017). In this research is only the relative effect of a nanocoating containing a single nanoparticle relative to other nanocoatings and an epoxy coating considered. Combinations of multiple nanoparticles in one nanocoating could also be investigated in further research. At last, this research is conducted by one person. To increase the robustness, more researchers should give the same scores.

6.2.2 Filtering of nanocoatings

Due to time limitations, the overview of nanocoatings is filtered on the self-cleaning ability of nanocoatings by photocatalyse. However, other nanocoatings containing no photocatalytic activity could perform well on the key performance indicators. Besides, organic polymers and more ceramics and carbon-based materials could be added to the overview to increase comprehensiveness.

6.2.3 Technical parameters

Factors that are not considered in this research are wt% of the nanoparticles in the nanocoating (Ali et al., 2021), thickness of the nanocoating (Ali et al., 2021), different conventional coatings that were used in the researches, coating materials on which nanocoatings were added, choice of film material and film formation and the application method of the nanocoating to the surface. From laboratory tests can be obtained that all these factors have a significant influence on the performance of the nanocoatings on the technical parameters(Ali et al., 2021) (Benitha et al., 2017). Therefore, these factors should be included in future research to obtain more accurate results. Moreover, the technical parameters are considered independent. However, in practice, is adhesion positively correlated with wear resistance and corrosion resistance and porosity is negatively correlated with corrosion resistance.

Furthermore, wear and corrosion resistance and porosity are not tested on concrete surfaces in every research due to unavailable literature, limiting the accuracy of the results. Therefore, practical quantitative research is required to apply different nanocoatings on concrete with equal circumstances. Then, a more accurate comparison can be made in between the nanocoatings and the epoxy coating on technical parameters.

6.2.4 Financial parameters

Only TiO_2 and SiO_2 nanocoatings are currently available to apply on concrete substrates. This research could not obtain an exact purchase price from the TiO_2 nanocoating due to the seller's intellectual property. Furthermore, the SiO_2 nanocoatings do still not function as a construction nanocoating in the market. Currently, no suitable nanocoatings are available for concrete surfaces in the market, indicating that nanocoatings are still a new technology in the market. The technology is still at the beginning of the early adapters stage of the life cycle of technology adaption, in which prices are high(Aslani et al., 2019). As weight percentages are included in laboratory research, the cost of raw nanoparticles indicates the mutual relationships of nanocoatings. However, it is too early for Koninklijke Oosterhof Holman to apply nanocoatings as not enough information is available yet on the purchase cost. Hence, a more comprehensive market analysis on the purchase price and the cost method of applying nanocoatings is required.

6.2.5 Toxicity parameters

Cytotoxicity of nanoparticles that are added to human, animal and plant cells are determined. However, whether equal amounts of nanoparticles will arrive in living cells in practice is still unknown. Additionally, the conducted research is based on the short-term effects of cytotoxicity in the cells. Whether nanoparticles are toxic in the long term is still to be investigated.

6.3 Theoretical implications

The degree of photocatalytic effect per nanocoating is not considered. It is only stated that the depicted nanocoatings can function as a photocatalyst. Still, the success of photocatalysis differs per nanomaterials and depends on factors as band gap energy, surface area/structure, light intensity, temperature and pH(Tahir et al., 2020). In future research, the degree of photocatalytic effect should also be considered as a technical parameter.

6.4 Practical implications

This research has contributed to the awareness that there is limited knowledge for nanocoatings with respect to cytotoxicity and purchase and application costs. Also, if one is to compare the different nanocoatings, it is recommended to have similar tests for the technical parameters such that quantitative analysis is better aligned. Currently, only different laboratory tests are available for different nanocoatings. Since epoxy coatings serve for ten years on concrete surfaces, more research is required to test nanocoatings' long-term effectiveness. Furthermore, literature research is limited to applying nanocoatings on concrete surfaces. Therefore, it can be stated that Koninklijke Oosterhof Holman should start coating reinforced concrete Dutch public artworks with epoxy coatings. It is too early to adapt nanocoatings as information on the total cost and cytotoxicity is lacking. However, nanocoatings show improving results on the technical parameters compared to the epoxy coating. Therefore, Koninklijke Oosterhof Holman should continue on investigating nanocoatings on concrete surfaces. Especially metal-oxides as MgO and TiO_2 are interesting for further investigation, according to table 3. For the University of Groningen, this implies that research on nanocoatings should also focus on the long-term effects of the defined cytotoxicity and the costs of nanocoatings when industrially available. Furthermore, for researchers, it should also be known that more focus should be put on the industrial application of nanocoatings.

7 Conclusion: nanocoatings not yet applicable on reinforced concrete Dutch public artworks

This research aimed to create an overview of nanocoatings compared with a conventional coating to apply on reinforced concrete Dutch public artworks via literature research. The nanocoatings are filtered on the ability of photocatalytic activity and availability of the nanocoatings in literature research. After the filtering process, metal-oxide nanocoatings and carbon-based nanocoatings are assessed on technical, financial and toxicity parameters. The following research question is formulated to test the suitability of nanocoatings on reinforced concrete Dutch public artworks:

Which nanocoatings score the highest rating on the defined technical, economic and toxicity parameters for application on reinforced concrete Dutch public artworks?

The results show that TiO_2, SiO_2, MgO, Al_2O_3 and carbon nanotube nanocoatings score higher than the epoxy coating, according to the qualified rating matrix. Moreover, all the nanocoatings are higher rated on technical parameters than the epoxy coating. However, the available literature is currently insufficient to assess nanocoatings on reinforced concrete Dutch public artworks accurately. The exact purchase cost and the long-term toxicity of nanocoatings are presently unknown. Additionally, the technical parameters are qualified on too many different tests with too many variables untreated in the rating to give an accurate overview.

To conclude, this research serves as an initial starting point for Koninklijke Oosterhof Holman on the research of nanocoatings. Quantitative research for industrial applications of nanocoatings applied on concrete surfaces is required to determine whether nanocoatings can apply to reinforced concrete Dutch public artworks.

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