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RECENT ADVANCES IN ANTICORROSIVE PHOSPHATE PIGMENTS

BY

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Abstract. This study presents the anticorrosive properties of certain types of phosphate pigments. Anticorrosive inorganic pigments are one of the most studied categories of pigments because, according to the existing data, nearly one-third of the world's metal production is out of use due to corrosion. Damage due to corrosion is often related not only to the loss of metal but also to the decommissioning of entire installations, whose processing and installation is spent more than the cost of the material from which they are made. The development of new products with anticorrosive action requires an understanding of the theoretical principles - fundamental chemistry, as well as the parameters that influence the processing techniques. In addition, this review will also summarize the most promising phosphates solutions (classes of compounds, physicochemical properties, methods of obtaining, anticorrosive efficiency) for corrosion protection of steel, aluminium, other materials and their alloys. It also briefly presents future directions for the manufacture of anticorrosive pigments such as submicron anticorrosive pigments, smart coatings (*e.g.*, corrosion sensing) or nanotechnology.

Keywords: anticorrosive inorganic pigments; corrosion environments; phosphate pigments.

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1. Introduction

Corrosion is the natural phenomenon that causes the partial or total destruction of materials in general and metals in particular, as a result of their interaction with the environment. As a spontaneous phenomenon, metal corrosion cannot be suppressed, stopped, but can be diminished. This is achieved by applying protective measures that slow down, inhibit physical, mechanical, chemical or biological processes of material destruction (Pfaff, 2017; Popov, 2015). The totality of the measures used to protect materials from the destructive action of interactions with environmental agents is known as anticorrosive protection. Corrosion behaviour of metallic materials in aggressive environments is essential for a modern society and care for the environment. For developed countries, economic financial damages due to corrosion involving the maintenance, repair and replacement of existing infrastructure amount to up to 4% of gross domestic product (GDP) (Bastidas, 2020).

Among the many anti-corrosion protection measures of materials, a special and important place is assigned to the protective coatings of varnishes and paints. This method is one of the oldest anti-corrosion protections measures of metallic and non-metallic surfaces. Varnishes, like paints are suspensions of natural or synthetic pigments, and various fillers, in a binder, the main component of which is a film-forming substance (vegetable oil, natural or synthetic resin).

The passive or active action of paint or coating film is primarily due to the nature and chemical composition of the pigment, plus the physical-chemical characteristics of the binder, as well as the state of the metal surface.

Pigments used in the preparation of paints and varnishes added primarily to protect surfaces from the corrosive action of the environment are referred to as anti-corrosive pigments.

The anti-corrosive pigments, according to their surface protection, can be divided into three categories: ***pigments with physical protection action*** (passive or inactive pigments, as Fe_3O_4 , (Buxbaum and Pfaff, 2005); ***pigments with chemical protective action*** (are called *active pigments*) - they contain soluble compounds and can maintain a constant pH value in the coating film; their action depends on the reactions taking place at the separation surface between the pigment and the substrate, between the pigment and the binder, for example, ZnO or Pb_3O_4 . Redox reactions occurring may lead to the formation of compounds which exhibit / exert a protection (oxides or hydrated oxides which may contain pigment cations) (Austin, 1993; Jašková and Kalendová, 2012; Pfaff, 2017). The last category of anti-corrosive pigments is represented by ***pigments with protective electrochemical action*** - pigments that prevent corrosion by forming a protective film (e.g. **phosphate pigments**); these are considered to be active in the anodic metal protection field, so-called *anode*

protection (Alibakhshi *et al.*, 2013; Pfaff, 2017) and also pigments that prevent rust formation due to the high potential of the standard oxidation potential (*e.g.* chromates) are considered to be active in the cathodic field, thus *cathodic protection* (Havlik *et al.*, 2007).

Corrosion of iron can be explained by its position in the electrochemical series of elements. In the ordinary steel ($\epsilon_{Fe/Fe^{2+}} = -0.44V$), (which is the most commonly used metallic material), anode and cathode zones are present, due to the phases existing in its structure, phases made of iron, carbon and oxides. These latent local areas are activated by aggressive reagents: moisture, oxygen and electrolytes, which generate electrochemical reactions between anode (consisting of iron) and cathode (carbon and oxide) zones. Anticorrosive active pigments, participating in the reactions, inhibit one or both electrochemical reactions.

Active chemical protection is located at the interface between the substrate and the paint layer. The water that diffuses into the binder, dissolves the soluble components (*e.g.*, phosphate, borate or organic anions) moves them away from the pigment particle and transports them to the surface of the metal where it reacts with it. Oxides, iron hydroxides or insoluble compounds (phosphates, chromates) formed on the surface of the metal, block the access of aggressive agents to cathodic and anodic zones, thereby breaking the corrosion. A new stream of water will penetrate harder through the film, and even if it participates in the formation of new amounts of hydroxides, it adds to the already existing film, consolidating it, or sometimes reacting, thus modifying it chemically. In this way, possible scratches on the surface of the film are repaired with active substances. Inhibition by forming a protective film is the most important action mode of anti-corrosive pigments (Buxbaum and Pfaff, 2005).

2. Metallic Phosphate Pigments

The anticorrosive protective action of phosphates is mainly achieved by metallic phosphates but also by organic phosphates, such as polyaniline phosphate or polypyrrole phosphate (Kalendova *et al.*, 2016). Pigments in this group are used for the corrosion protection of ferrous metallic materials. After applying a paint containing a phosphate (*e.g.* zinc phosphate), chemical interactions occur on the surface of iron. The most important interaction is that which ultimately leads to the formation of a complex combination of $[Zn_3(PO_4)_3]^{3-}Fe^{3+}$ form. It forms an adherent and compact layer, combining directly on the metal surface. Some researchers advanced the idea that at the metal-film interface, a basic iron complex is formed when the pigment contains crystallization water, also adherent to the surface. The pigment reacts with the binder, more preferably with the acidic groups in the binder, forming soaps, which sometimes adversely affects the adhesion of the film or causes gelling.

In Table 1 the most commonly used metallic phosphates pigments are presented.

Table 1
The Most Used Metallic Phosphate Pigments

| Pigment | Protected metal | Characteristics | References |
|--|-----------------|---|---|
| Zinc phosphate $Zn_3(PO_4)_2 \cdot xH_2O$ and mixtures | iron | Superhydrophobic, nanoparticles, imidazole encapsulated, hollow zinc phosphate incorporated in epoxy resin; anticorrosion performance was evaluated by electrochemical impedance spectroscopy (EIS) measurements. | Jadhav <i>et al.</i> , 2018 |
| | | epoxy coatings containing different concentrations of submicron-sheet zinc phosphate pigment; protection performances were measured by EIS; | Shi <i>et al.</i> , 2019 |
| | | benzotriazole and graphene oxide co-modified zinc phosphate, excellent corrosion inhibition performance, the released Zn^{2+} and PO_4^{3-} can connect with metal substrate forming complicated and compact passive film slowing down the diffusion of corrosive ions; anticorrosive properties measured by electrochemical impedance spectroscopy (EIS) and polarization curve tests; | Xue <i>et al.</i> , 2019 |
| | | Standard zinc phosphate and organophilized zinc molybdate phosphate, white-beige, used in oil-, alkyd- and epoxy-ester-based primers; investigated by traditional salt spray (NSS) and electrochemical - accelerated cyclic electrochemical test (ACET). | Gimeno <i>et al.</i> , 2014; Jašková and Kalendova, 2012 |
| | | zinc aluminium phosphate and zinc aluminium polyphosphate, in epoxy/polyamide coating, the (EIS) and salt spray test used to investigate the performance of coating | Mousavifard <i>et al.</i> , 2013; Naderi and Attar, 2010 |
| | | potassium zinc phosphate (synthesized through a co-precipitation method) reduced corrosion current density and shifted corrosion potential toward positive values Corrosion inhibition studied by linear polarization test and polarization measurements. | Askari <i>et al.</i> , 2015 |

| | | | |
|--|-----------------|---|---|
| | | zinc aluminium molybdenum orthophosphate, zinc calcium strontium aluminium orthophosphate show corrosion inhibition synergism; EIS and polarization measurements; | Naderi <i>et al.</i> , 2014 |
| | | lithium zinc phosphate, superior corrosion inhibition effect, sodium zinc phosphate pigment (synthesized by co-precipitation), EIS, salt spray and wet pull-off tensile strength monitoring; | Alibakhshi <i>et al.</i> , 2013 |
| Aluminium phosphate $\text{AlPO}_4 \cdot n\text{H}_2\text{O}$ and mixtures | iron | Aluminium phosphate, aluminium tripolyphosphate ($\text{AlH}_2\text{P}_3\text{O}_{10} \cdot 2\text{H}_2\text{O}$), ferric phosphate ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$), calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$), barium phosphate and hydrogen barium phosphate (BaHPO_4) and ferrous ammonium phosphate ($\text{FeNH}_4\text{PO}_4 \cdot 2\text{H}_2\text{O}$), calcium and strontium aluminium phosphates - $\text{SrHPO}_4 + \text{CaHPO}_4$ (average particle size 270–400 nm), monitoring by electrochemical noise tests. | Chromy and Kaminska, 1990; Pfaff, 2017; Przywecka <i>et al.</i> , 2018; Song <i>et al.</i> , 2015 |
| | | Strontium aluminium polyphosphate average particle size 2.0–3.5 μm , average density 2.9 $\text{g}\cdot\text{cm}^{-3}$, oil absorption 40g/100g, EIS and leaching measurements. | Emad <i>et al.</i> , 2019 |
| Calcium phosphate $\text{Ca}_3(\text{PO}_4)_2$ and mixtures | iron | Calcium zinc phosphate $\text{CaZn}_2(\text{PO}_4)_2$ in nanocontainer for active anticorrosion coatings, corrosion analysis by monitoring Tafel plot ($\log I $ vs. E). | Bhanvase <i>et al.</i> , 2013 |
| | | Calcium acid phosphate with small amount of lanthanum molybdate, corrosion rates determined by the polarization resistance technique, the anticorrosive performance monitoring through accelerated tests and electrochemical tests. | Roselli <i>et al.</i> , 2017 |
| $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}/\text{ZnO}$; $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}/$ $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$ Mg/Ca phospho-molibdates | iron, aluminium | Different pigments formulation applied on standard low-carbon steel panels S-46, tested with good results for Cyclic corrosion test in an environment containing sulfur dioxide, neutral salt spray or in environment containing water condensed vapor; immersion in electrolyte (3.6% $(\text{NH}_4)_2\text{SO}_4$ with 1.5% NaCl) and SO_2 exposure. | Buxbaum and Pfaff, 2005; Jašková and Kalendová, 2012 |

| | | | |
|---|---------------------------------------|--|---|
| magnesium phosphate | magnesium alloy, iron or zinc | A mixed iron–manganese orthophosphate $(\text{Mn,Fe})_5\text{H}_2(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$, the anticorrosive properties and mechanical resistance compared with zinc phosphates; $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$ as new beryite, orthorhombic structure. | Duszczuk <i>et al.</i> , 2018; Ishizaki <i>et al.</i> , 2009 |
| $\text{Na}_5\text{P}_3\text{O}_{10}$ | iron | Sodium tripolyphosphate - waterborne epoxy (EP) coatings were modified by incorporating sodium tripolyphosphate pillared layered double hydroxides, EIS measurements. | Wang <i>et al.</i> , 2019 |
| $\text{Sr}_3(\text{PO}_4)_2$ and $\text{Ba}_3(\text{PO}_4)_2$ | iron - reinforced concrete structures | Pigments produced using core shell methods; measurement by elcometer analysis, open circuit potential measurement, half-cell potential measurement and EIS were conducted and the results were recorded. | Ananthkumar and Mini, 2019 |
| barium phospho-silicate | iron | HALOX® BW-111 is a low-cost barium phosphosilicate-based corrosion inhibitor designed for long-term corrosion protection. It is designed to provide mid-level corrosion protection in light-duty industrial coatings such as high solids epoxies. | https://www.halox.com/halox-bw-111/ ; Pfaff, 2017 |
| chromates phosphates polyphosphates | iron | $\text{Cr}(\text{PO}_3)_3$, $\text{CoCr}_2(\text{P}_2\text{O}_7)_2$ - $\text{Co}_3\text{Cr}_4(\text{PO}_4)_6$ anticorrosive ceramic pigments. | Luxova <i>et al.</i> , 2019; Pfaff, 2017 |

2.1. Zinc Phosphate

Zinc phosphate $\text{Zn}_3(\text{PO}_4)_2 \cdot (2-4)\text{H}_2\text{O}$ has been the standard non-toxic pigment used instead of chromates. It is the most important pigment in the phosphate group. The great advantage of zinc phosphate is that it can be easily produced in various forms; it has low solubility, reactivity comparable to chromates or other anticorrosive phosphates and can be used in multiple anticorrosive formulations. Zinc phosphate is extremely versatile; it can be used in different binder, as oil-based binders, epoxies and alkyds, for which other pigments have stability problems, the loading percentage varying between 10-30%.

Because on the market, there are many types of anticorrosive pigments based on zinc phosphate, it was formally agreed to be grouped into classes (depending on the chronological appearance). The first generation is $\text{Zn}_3(\text{PO}_4)_2$, which is limited due to its low solubility, only a small amount of phosphate is available for metal protection. The second generation consists of classical zinc phosphate ($\text{Zn}_2(\text{OH})\text{PO}_4 \cdot 2\text{H}_2\text{O}$), plus metal phosphates and orthophosphates

(zinc aluminium phosphate, hydrated zinc molybdate), the third generation includes zinc polyphosphate, combined with aluminium phosphate and strontium, and calcium silicate additives).

Zinc phosphate pigment provides corrosion protection through several mechanisms (Knudsen and Forsgren, 2017):

- donating phosphate ions, in humid atmosphere, for ferrous materials, with the formation of $Zn_5Fe(PO_4)_2 \cdot 4H_2O$;
- the formation of protective films on the anode, the dissolved oxygen in the film is absorbed in the metal, undergoes a heterogeneous reaction to form a protective film of Fe_2O_3 of about 20 nm, the film prevents the external diffusion of iron, even if the phosphate ion does not appear to contribute directly to the formation of the oxide film;
- polarization of the substrate.

For example, the anticorrosive protection of zinc phosphate mechanism is especially of chemical nature and is presented in Fig. 1.

The intermediate steps of achieving corrosion protection for iron-based materials with zinc phosphate are:

- at the anode, on the metal surface, iron ionization: $2Fe \rightarrow 2Fe^{2+} + 4e^-$
- at the cathode, on a metal surface, oxygen reduction: $O_2 + H_2O + 4e^- \rightarrow 4HO^-$;
- zinc phosphate, hydrolyses in binder, forming gelatinous zinc hydroxide and monoacid phosphate anion: $Zn_3(PO_4)_2 \cdot 2H_2O + 4HO^- \rightarrow 3Zn(OH)_2 + 2HPO_4^{2-}$;
- the acid phosphate anion reacts with iron ions and forms iron monoacid phosphate, which attaches to the metal surface protecting it;
- zinc hydroxide often strengthens the iron phosphate layer (in case of insufficient moisture).

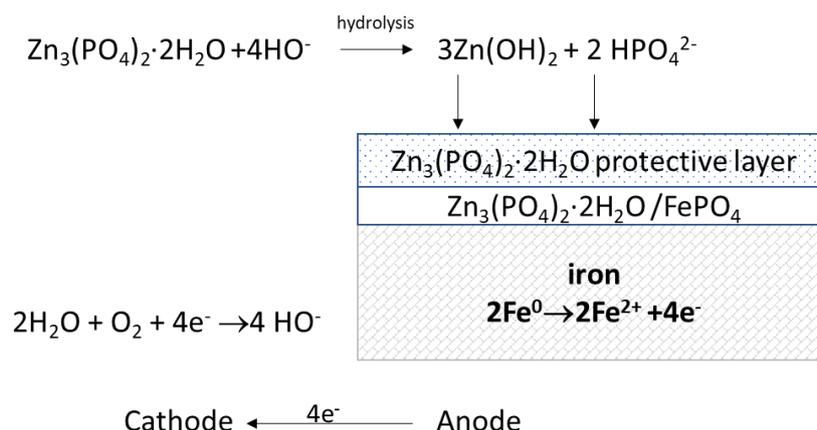
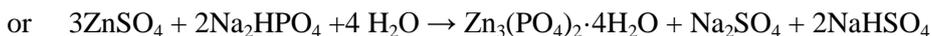


Fig. 1 – Passivation of iron by zinc phosphate
(adapted after Buxbaum and Pfaff, 2005).

It is manufactured industrially by the direct method using as starting material zinc oxide or zinc sulphate and phosphoric acid or disodium phosphate according to the chemical equations:



More often used are zinc sulphate and disodium phosphate, because by modifying some parameters in the manufacturing process, pigment particles of optimum size are obtained. Also, best results are obtained when solutions are diluted up to 10% and temperatures of 20 - 25°C are used. The pH value of the reaction mixture exhibits a great influence on the particle size. For this reason, NaOH is added to the reaction medium to adjust the pH to 5.8 - 6.2, when fine particles of 0.5-1 µm are obtained. Above this pH value, colloidal particles are formed due to the formation of a large amount of zinc hydroxide. If NaOH is not added to the system, the pH of the reaction mixture is slightly acidic (3.5-4) and results in large particles of 40-80 µm.

The pigment formed in the reaction mixture is separated by decantation, then by filtration. The cake is washed 3 to 4 times with water to remove sulphate anions (less than 0.1%), chlorine (less than 0.01%) and soluble components (less than 0.1%). Zinc phosphate is white-beige, crystallizes in rhombic system and has a low solubility in water or alcohol. It has a specific weight of 3200 kg/m³ and a small oil index of 20 g / 100g.

The anticorrosive action of zinc phosphate is influenced by particle size, the lower size, the better the efficiency. When the particle size exceeds 4 - 5 µm, micronize it.

Zinc phosphate is used for the preparation of primer paints, which is applied as the first layer on the surface of ferrous materials. Having a light colour, the primer coat may be covered with layers of light film coatings.

But, along with traditional methods of preparation, more and more researchers are turning to specific methods, aiming to the preparation of nanoparticles, core-shell assemblies or encapsulations in various polymer matrices. The synergetic action of several cations was also followed and tested by classical methods (testing in fog chambers) or instrumental - electrochemical technique (accelerated cyclic electrochemical technique). To increase the protective behaviour of zinc phosphates, a "second generation" pigment based on zinc phosphate was designed by combining elements such as molybdenum or aluminium (Gimeno *et al.*, 2014).

From the point of view of toxicology and occupational health, zinc phosphate falls into risk categories R50 / 53 and S60 / 61 (2004/73 / EU), and may cause long-term adverse effects in aquatic environments. So, special measures are required for processing, storage and disposal of this product.

2.2. Aluminium Zinc Phosphate

The commercial aluminium phosphate pigment, contains zinc and aluminium phosphate with 35-39% Zn, or aluminium and zinc triphosphate, with 11.6-14.9% Zn. The aluminium phosphate anticorrosive pigment is sold in the form of three assortments containing variable amounts of zinc:

- aluminium triphosphate -1, with 5.5-7.7% Al and 11-14.9% Zn;
- Aluminium commercial triphosphate - 2, with 4.7 - 6.9% Al and 21 - 24.5% Zn;
- Zinc and aluminium hydrated phosphate - 3, with 4-5% Al and 35-39% Zn.

Zinc and aluminium hydrate phosphate are prepared by precipitation by reacting aluminium acid phosphate and zinc oxide.

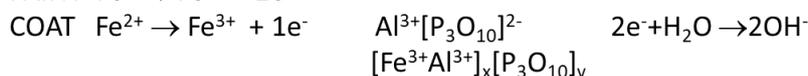
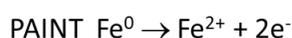
The reaction conditions determine the composition and properties of the pigment, respectively. For the white pigment, with the increase of the percentage of Zn, the specific gravity increases, 3000 - 3200 kg/m³, the oil absorption index decreases slightly, 35 - 30, and the pH value decreases 7 - 6.5 - 6, and the particle size remains approximately constant, about 1 μm. After the reaction, the white pigment was filtered off, washed and dried. All three assortments are used to obtain primer paints, as the first protective layer, a layer that has a good adhesion to the metal surface.

2.3. Aluminium Phosphates

Anti-corrosion pigments based on aluminium phosphate (AlH₂P₃O₁₀·2H₂O) have been used since 1970.

Thus, the [P₃O₁₀]⁵⁻ anion (AlH₂P₃O₁₀ → Al³⁺ + 2H⁺ + [P₃O₁₀]⁵⁻) reacts with iron to form an insoluble layer of ferric triphosphate, with very good adhesion to the metal substrate. It is considered that aluminium phosphate provides corrosion protection according to the following mechanism (Chromy and Kaminska, 1990), presented in Fig. 2.

Dissolved oxygen in water



anodic part pure iron surface cathodic part

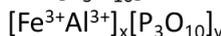
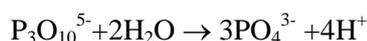
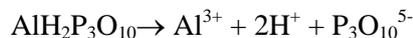


Fig. 2 – Passivation of iron by aluminium phosphate.

According to Song *et al.*, (2015) the adhesive film with anticorrosive properties is formed according to the following mechanism:



Compared to other non-toxic pigments, such as zinc phosphate or molybdate, aluminium phosphate has a greater ability to inhibit corrosion, but its anticorrosive properties can be increased by combining with zinc or silica.

2.4. Chromium Phosphate $\text{CrPO}_4 \cdot 3\text{H}_2\text{O}$

The chromium (III) phosphate pigment is obtained by precipitation from the reaction of the trisodium phosphate solution with a trivalent chromium (chloride or sulphate) salt. Chromium (III) is considered non-toxic. Chromium phosphate crystallizes in the triclinic system, has a green-violet colour, a specific surface area of $22 \text{ m}^2/\text{g}$, an oil index of $65 \text{ g} / 100 \text{ g}$ and contains about 27% Cr and 47% phosphate, pH 6.5, $500 \mu\text{S}$ electrical conductivity.

It is almost always used in combination with other anti-corrosive pigments because it has a low solubility. It is a highly protective pigment (long-term corrosion inhibitor), the reaction mechanism is shown in Fig. 3, but is poorly effective in the first phase of anti-corrosion protection.

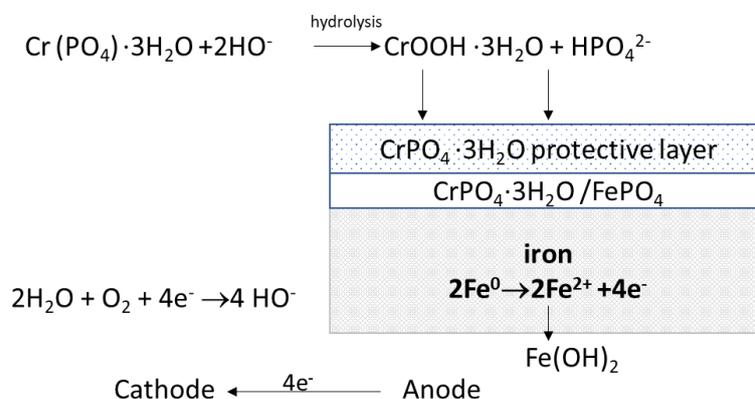


Fig. 3 – Passivation of iron by chromium phosphate.

Even if chromium (III) phosphate is slightly soluble in water, overexposure to this compound could have harmful effects. The toxicity of chromium (III) phosphate depends on the duration of exposure, on the concentration of chromium (III) phosphate, and also on the routes of entry and the release of the trivalent chromium ion from chromium (III) phosphate.

2.5. Other Metallic Phosphates

In addition to the previously mentioned anticorrosive phosphate pigments, which are obtained in large quantities and have industrial applications, other pigments are also produced, but in small quantities due to colour, preparation difficulties, cost price and toxicity. Some of the new pigments have commercial names, but the chemical composition and their production are covered by patents. Such pigments are manganese phosphate, $Mn_3(PO_4)_2 \cdot 3H_2O$; ferric and ammonium phosphate, $FeNH_4PO_4$, greenish-yellow; barium phosphate, $Ba_3(PO_4)_2$, white version, pyrophosphate, $BaCr_2(P_2O_7)_2$ as a green pigment with high NIR solar reflectance or cerium phosphate (Ananthkumar and Mini, 2019; Ishizaki *et al.*, 2009; Jose *et al.*, 2019; Morozov *et al.*, 2019).

The high efficiency of corrosion inhibition of metallic phosphate pigments required the initiation of research to obtain new products with specific uses. In this sense, the aim was modification of some anions (mixtures with phosphovanadates and phosphocarbonates have good anticorrosive activity), inclusion of new cations (Mg, Fe, Ca), optimizing the particle size distribution or accumulation of phosphates with synergistic effects. Recently, corrosion sensors have been developed, with very small dimensions, which can be incorporated in various devices, with the role of warning in case of unwanted corrosion process (Wright *et al.*, 2019). The aim is to create anti-corrosion pigments that will also function as corrosion sensors.

3. Conclusions

Anticorrosive pigments are an important class of functional inorganic pigments. They are mainly characterized by anticorrosive properties while appearance and colour play a secondary role. The most used are those based on zinc phosphate mixed with calcium or aluminium phosphate and additions of other components (vanadates, molybdates, oxides, silicates).

Anticorrosive pigments are very important in reducing the costs caused by corrosion; their efficiency depends strongly on their interaction with the binder, and can be designed for specific uses.

The aspect regarding their toxicity is also important, thus, pigments containing carcinogenic or highly toxic components are limited for use or their replacement is sought.

The next generations of phosphate-based anticorrosive pigments aim to develop chromate-free and heavy-metal-free formulations, with a focus on the development of sub-micron pigments, smart coatings (which allow, for example, corrosion detection) and the involvement of nanotechnology.

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STADIUL ACTUAL AL PIGMENȚILOR ANORGANICI ANTICOROZIVI PE BAZĂ DE FOSFAȚI

(Rezumat)

Acest studiu prezintă proprietățile anticorozive ale unor tipuri de pigmenți pe bază de fosfați. Pigmenții anorganici anticorozivi sunt una dintre cele mai studiate categorii de pigmenți, deoarece, potrivit datelor existente, aproape o treime din producția de metale din lume nu este utilizată din cauza coroziunii. Deteriorările datorate coroziunii sunt adesea legate nu numai de pierderea de metal, ci și de dezafectarea instalațiilor întregi, a căror prelucrare și instalare costă mai mult decât prețul materialelor din care sunt fabricate. Dezvoltarea de noi produse cu acțiune anticorozivă necesită o înțelegere a principiilor teoretice - chimie fundamentală, precum și a parametrilor care influențează tehnicile de procesare. În plus, în această lucrare se prezintă cele mai promițătoare soluții pe bază de fosfați (clase de compuși, proprietăți fizico-chimice, metode de obținere, eficiență anticorozivă) pentru protecția la coroziune a oțelului, a aluminiului, a altor materiale și a aliajelor acestora. De asemenea, se prezintă succint direcțiile viitoare pentru fabricarea pigmenților anticorozivi, cum ar fi pigmenți anticorozivi submicronici, acoperiri inteligente (de exemplu, senzori de coroziune) sau soluții bazate pe nanotehnologie.