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Investigating sodium phosphate binders for foundry production

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ABSTRACT

The results of theoretical and practical research on the synthesis of sodium phosphates from its inorganic salts and the use of these phosphates as binders for the manufacture of molds and cores are presented.

In order to find variants of sodium phosphate synthesis, the processes of interaction of orthophosphoric acid H_3PO_4 with sodium salts of different types (Na_2CO_3 carbonate (salt of chemically weak acid), NaCl chloride (salt of chemically strong acid) and tripolyphosphate $Na_5P_3O_{10}$ (polyphosphoric salt)) were analyzed. The regularities of the formation of sodium phosphates in all three systems and the conversion of these phosphates when heated in the range from 20 to 1000 °C have been researched.

For the first time, thermodynamic parameters were established and the process of obtaining sodium phosphate through the chemical interaction of orthophosphoric acid with sodium chloride was implemented in the laboratory.

It has also been shown that the chemical interaction of sodium tripolyphosphate with orthophosphoric acid forms the strongest binder, which is a disodium pyrophosphate $Na_2H_2P_2O_7$.

Synthesized sodium phosphates have an optimal set of functional properties for using in foundry technologies. They provide high strength in compositions with refractory quartz filler and have sufficient thermal stability. Experimentally established, foundry cores based on synthesized binders provide high quality cast surfaces and are easily removed from the internal cavities of cast parts.

1. Introduction

Foundry production is the basis of modern engineering and many other industries. Technical progress in the development of molding materials increases the quality and competitiveness of cast products for traditional and new alloys (Fesenko and Fesenko, 2020; Fesenko et al., 2014; Hryhoriev et al., 2018), and composite (Hryhoriev et al., 2017; Klochikhin and Naumyk, 2019).

The development of new and improvement of known inorganic binders is relevant from both point of view a scientific and practical (Grimzin et al., 2020; Ponomarenko et al., 2020). In recent years, the interest of phosphate materials has increased again, the study of which began in the middle of the twentieth century. The most significant scientific results belong to scientists from the Massachusetts Institute of Technology (USA) (Kingery et al., 1976; Kingery, 1950) and the Leningrad Technical Institute (USSR) (Sychev, 1974; Sudakas, 2008).

Phosphate binders, including new and improved, are used in many technical fields. For example, a complex of binders modified with aluminum, silicon and iron has found application in construction (Mimboe et al., 2020), aluminum phosphates are used to make porous ceramics based on silicon carbide (Yang et al., 2019).

The combination of such properties as high mechanical strength, thermal and chemical resistance, the ability to regulate hardening processes with the formation of crystalline or amorphous structure led to the use of phosphate materials in the most extreme conditions, in particular for the manufacture of refractory products and foundry cores (Liutyi et al., 2021). Such materials are successfully used for hulls and shafts of shell and plate shock absorbers, which are equipped for elastic suspensions of knockout and transport units automated lines of foundry (Velichkovich et al., 2018; Velychkovych et al., 2020).They also allow to provide thermal stability and contact wear resistance of detachable and non-detachable joints, which are operated in conditions of high temperatures and pressures (Shatskyi et al., 2020; Ropyak et al., 2021). Refractory products based on aluminosilicate filler and

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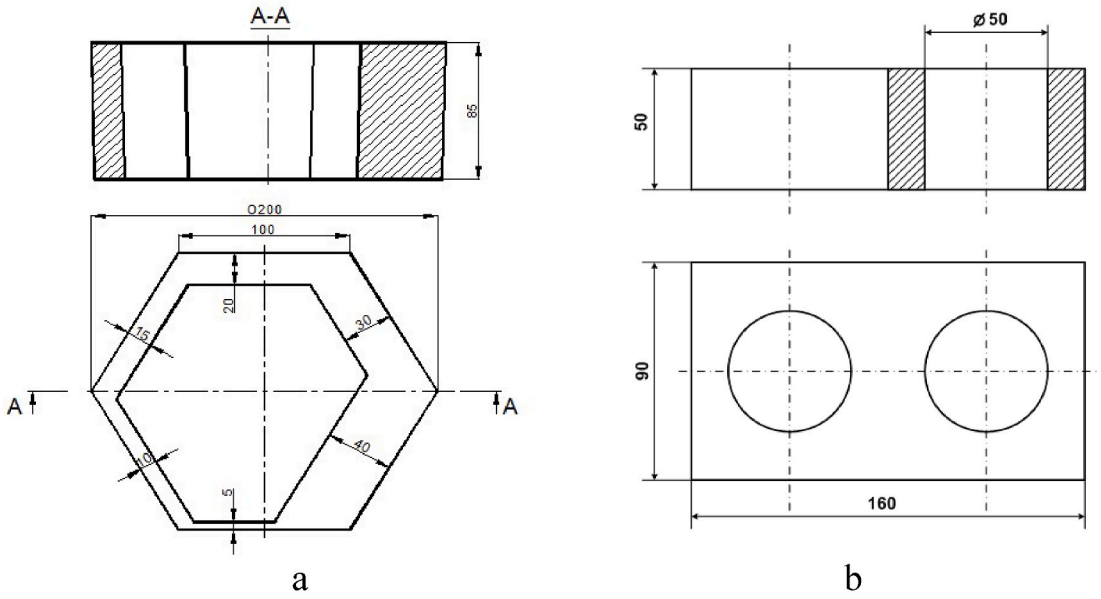

Fig. 1. Technological samples to determine the resistance of molding and core mixtures to burn (a) and the work of extracting cores from cast parts (b).

aluminophosphate or aluminum-magnesium phosphate binders are characterized by thermal stability of 1400 … 1600°C (Abyzov, 2016, 2017).

The addition of phosphates to calcium aluminate cement increases strength and thermal stability. The authors (Chavda et al., 2015) studied in detail the phase composition and transformation in this inorganic system.

By-products of other industries, in particular multicomponent inorganic materials, are often used to create phosphate compositions that cure when heated or at normal temperatures (Latutova and Svatovskaya, 2006; Osipenko et al., 2018; Illarionov et al., 2012; Volochko, 2013).

There is not much information about the synthesis and use of alkali and alkaline earth metal phosphates. In particular, the conditions of synthesis for calcium phosphates and their morphology were thoroughly studied in the article (Bashah and Noor, 2019). Sodium phosphates are actively used for the production of glass and composite materials with various special (optical or electrical) properties (Omrania et al., 2015; Liu et al., 2019; Yang et al., 2020). The possibility of using sodium phosphates for binders in high temperatures and aggressive environments, particularly in foundry production, has been insufficiently studied. Therefore, this group of non-scarce and environmentally friendly materials is not widely used in industry.

On the other hand, the global environmental problem of using sodium phosphates in household chemicals is widely known. Scientists from different countries note this leads to the rapid flowering of aquatic plants, and then to the mass death of hydrofauna (Ukraine and phosphates that kill us, 2018; Kryzhanovsky et al., 2011). Fresh water becomes unfit for drinking and life-threatening (Pochapsky, 2019). In addition, thousands tons of sodium phosphates fall into seas and oceans each year (Dubovy and Dubovy, 2016).

Austria, Germany, Italy, The Netherlands, Norway, Switzerland, Korea, Hong Kong, Thailand, South Africa, and several US states have banned phosphates in household chemicals; in Japan, phosphates disappeared from washing powders in the mid-1980s (Ukraine and phosphates that kill us, 2018). Obviously, the solution to this environmental problem is to remove phosphates from household chemicals. It is not possible to stop their production altogether, because they are by-products of the synthesis of phosphoric acids and mineral fertilizers, and their annual amount will not decrease significantly in the coming years. Therefore, the question to find new areas of application of significant amounts of sodium phosphates is acute. This requires further study of their structure and properties and also search for the best options for their synthesis.

1.1. *Formulation of research problems*

The aim of our study is to develop a technology for the synthesis of sodium phosphate binders with high levels of strength and thermal stability for the needs of foundry production and to study their composition, structure and properties.

1.1.1. *Research objectives*

1. To analyze the chemical and thermodynamic conditions of interaction for orthophosphoric acid H_3PO_4 and inorganic sodium salts. To establish theoretical preconditions for the synthesis of phosphate binders in these systems.
2. To investigate the chemical and phase composition of materials formed from a mixture of orthophosphoric acid with carbonate (Na_2CO_3), chloride (NaCl) and sodium tripolyphosphate ($Na_5P_3O_{10}$).
3. To analyze changes in chemical and phase composition during heating in the range of 20–1000 °C and predict the possibility of using mixtures of these materials for molds and cores in foundry.
4. To determine the physical and mechanical properties of molding and core mixtures based on quartz filler with binders synthesized from orthophosphoric acid and inorganic sodium salts.
5. To check the developed mixtures in terms of practical application. To establish the complexity of extraction of cores and quality of cast surfaces for undoped alloys based on iron.

2. Research methodology

X-ray qualitative and quantitative analysis was performed by the device « Rigaku Ultima IV».

Differential thermal analysis was performed by the device “STA 449 C Jupiter".

Technical thermal orthophosphoric acid of 85% concentration was used. Materials from inorganic sodium compounds were used in the work: carbonate Na_2CO_3, chloride NaCl, tripolyphosphate $Na_5P_3O_{10}$ and hexametaphosphate $(NaPO_3)_6$ of technical grade.

The strength of the molding and core mixtures was determined using a standard conventional technique in foundry by standard cylindrical

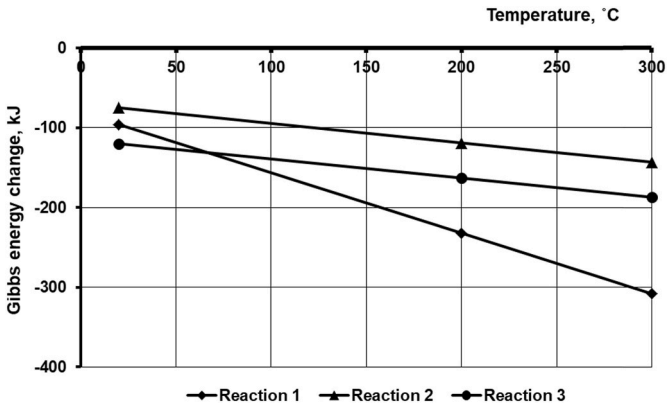

Fig. 2. The value of Gibbs energy for reactions (1)–(3) of the interaction of sodium carbonate with orthophosphoric acid in the range from 20 to 300 °C.

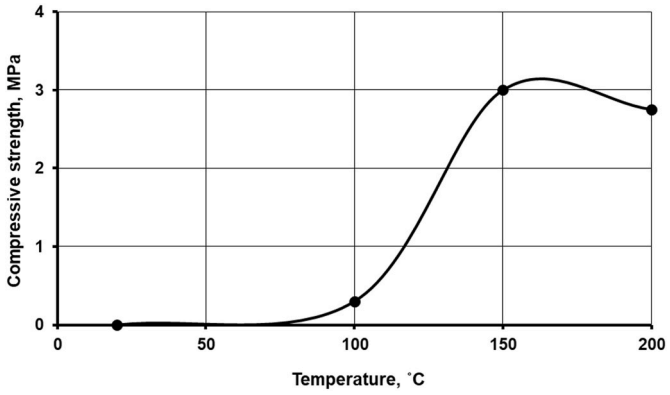

Fig. 3. The dependence of the strength of the sample (the mixture orthophosphoric acid, sodium carbonate and quartz sand) on temperature.

samples with a diameter and height of 50 mm. The samples were dried at the optimum temperatures determined by the research for 1 h.

Production of molds, cores, melting and pouring of iron-carbon alloys was carried out in the foundry laboratory of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute".

To determine the resistance of the core mixtures to burn, a technological sample of Nikolai Fyodorov was used. This is a casting with different wall thicknesses from 5 to 40 mm (Fig. 1, a).

The roughness of the cast surfaces was determined using the device Mobile profilometer contact type MAHR model MarSurf PS 10, with inductive support probe, tip needle radius 2 μm, measuring force 0.7 mN.

Knockout was controlled by the total work of extracting a standard sample from a technological sample (Fig. 1, b).

3. Experimental data

Sodium carbonate according to the general chemical classification is a weak acid salt, so it should react with orthophosphoric acid at normal temperature. First of all, it is possible following chemical reactions, which is also confirmed by thermodynamic analysis (Fig. 2):

$$3Na_2CO_3 + 2H_3PO_4 \rightarrow 2Na_3PO_4 + 3CO_2\uparrow + 3H_2O\uparrow \quad (1)$$

$$Na_2CO_3 + H_3PO_4 \rightarrow Na_2HPO_4 + CO_2\uparrow + H_2O\uparrow \quad (2)$$

$$Na_2CO_3 + 2H_3PO_4 \rightarrow 2NaH_2PO_4 + CO_2\uparrow + H_2O\uparrow \quad (3)$$

However, heating is necessary to strengthen the real mixture, which contains a refractory filler in addition to orthophosphoric acid and sodium carbonate, because water is a by-product of the chemical reactions. The maximum strength of the mixture, which contains 94 mass units of quartz sand, 3 mass units of orthophosphoric acid and 3 mass units of sodium carbonate, occurs at 150 °C (Fig. 3).

Differential thermogravimetric analysis was performed for the mixture of sodium carbonate and orthophosphoric acid (Fig. 4), which was previously thermal exposure at 150 °C. It is established that a number of physical and chemical transformations in the temperature range up to 700°C take place in the system.

Taking into account the results of thermal analysis, the quantitative and qualitative phase composition of the sample in the initial state (Fig. 5, a) and after heating to 700 °C (Fig. 5, b), ie after completion of all transformations, was determined.

X-ray phase analysis showed that sodium phosphates are indeed

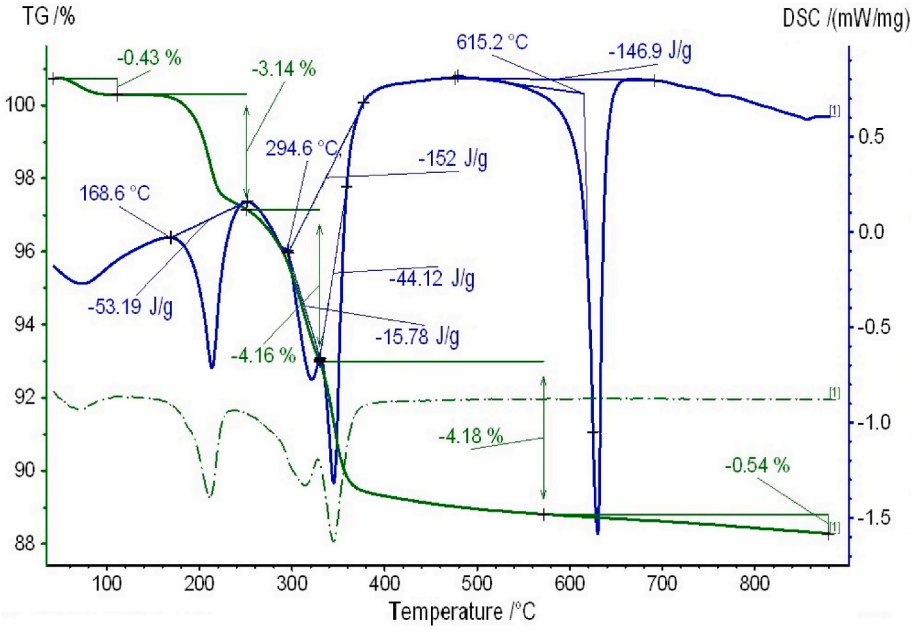

Fig. 4. Differential thermogravimetric analysis for the mixture of sodium carbonate (1 mass units) and orthophosphoric acid (1.5 mass units) after thermal exposure at 150 °C.

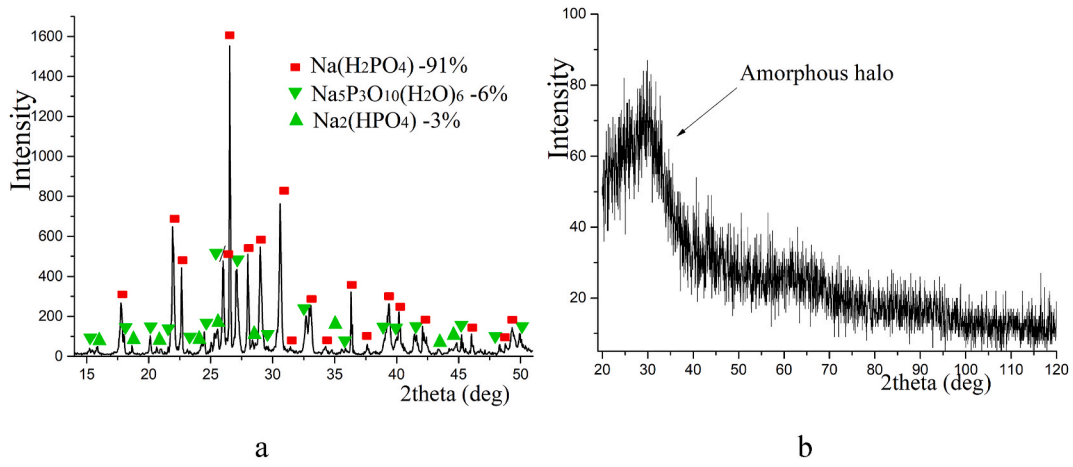

Fig. 5. X-ray phase analysis of the mixture of sodium carbonate (1 mass units) and orthophosphoric acid (1.5 mass units) after heat treatment at 150 °C (a) and at 700 °C (b).

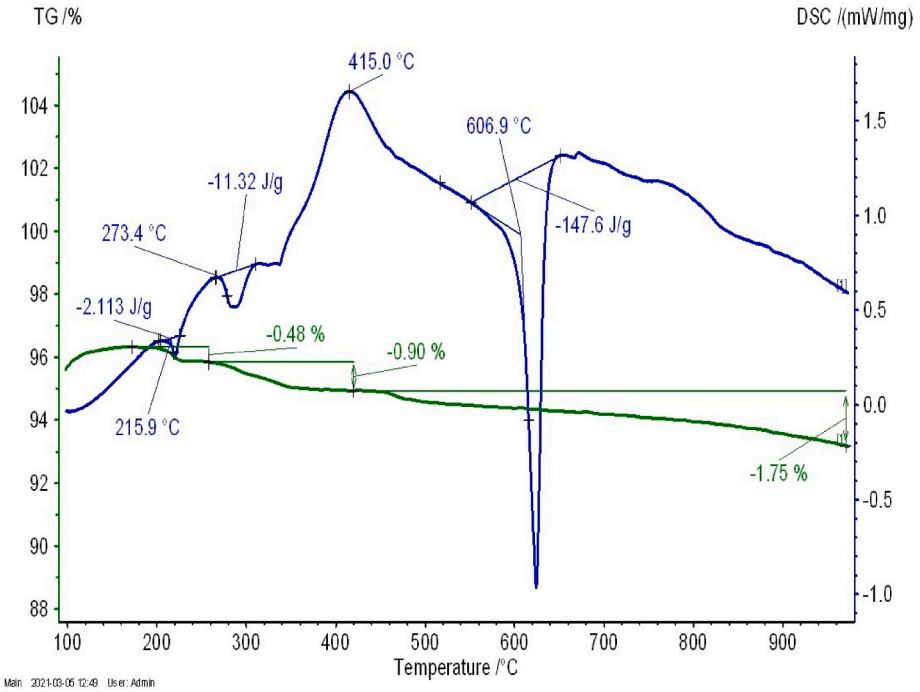

Fig. 6. Differential thermogravimetric analysis of technical sodium hexametaphosphate.

formed in these mixtures, of which monosodium phosphate NaH_2PO_4 (91%) predominates. It is formed by reaction (3). In addition, the sample contains a negligible amount of disodium phosphate Na_2HPO_4 formed by reaction (2). Also, a more complex form of sodium phosphate has been identified, namely sodium hexahydrate tripolyphosphate $Na_5P_3O_{10}{\cdot}6H_2O$. Apparently it was formed by the following chemical reaction:

$$5Na_2CO_3 + 6H_3PO_4 \rightarrow 2Na_5P_3O_{10} + 5CO_2\uparrow + 9H_2O\uparrow \quad (4)$$

Because the resulting mixture of sodium phosphates provides high strength samples with quartz filler, it can be attributed to phosphate binders. When this binders are heated, dehydration (168,6°C) of sodium hexahydrate tripolyphosphate occurs first.

The next two effects (or double endothermic effect), starting at 294,6°C, correspond to the conversion of acidic sodium phosphates. According to data (Lorent and Szeplaki, 1967; Lidin et al., 2000), acidic sodium phosphates after decomposition are converted mainly into metaphosphate. It follows reactions:

$$NaH_2PO_4 \rightarrow NaPO_3 + H_2O \quad (5)$$

$$2\ Na_2HPO_4 \rightarrow NaPO_3 + Na_3PO_4 + H_2O \quad (6)$$

The total weight loss after these transformations due to the removal of H_2O is near 14% (Fig. 4).

The greatest thermal effect is observed at 615,2°C. This is apparently due to the melting of sodium metaphosphate. After melting and re-solidification, it acquires an amorphous state, as evidenced by the diffraction pattern in Fig. 5, b.

The conclusion about the formation of sodium metaphosphate in the studied sample is confirmed by the result of differential thermal analysis of a separate technical sodium hexametaphosphate $(NaPO_3)_6$ (Fig. 6). This material is in an amorphous state under normal conditions. During heating, it turns into a crystalline state, which is confirmed by the exothermic effect at 415°C. And at 607°C its melting begins. This

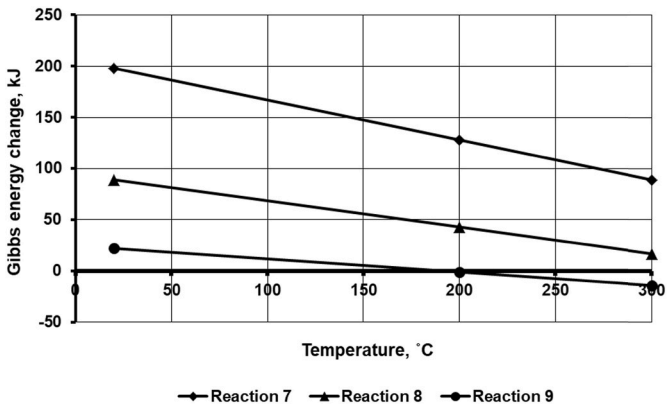

Fig. 7. Gibbs energy change in the range from 20 to 300 °C for the reaction of sodium chloride with orthophosphoric acid.

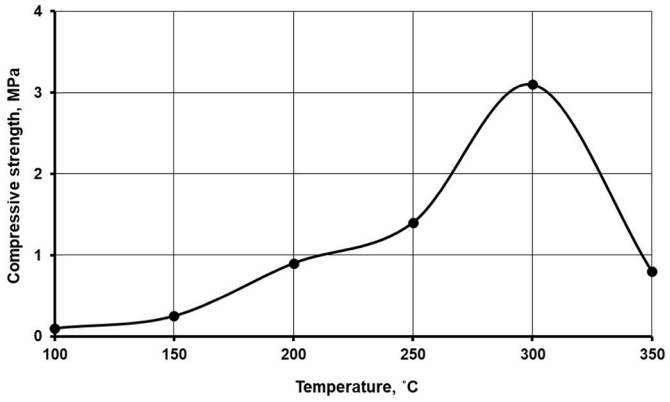

Fig. 8. The strength of the mixture sample of orthophosphoric acid and sodium chloride as a function of temperature.

temperature and the thermal effect of the conversion coincide with the data (Fig. 4).

The small difference in temperature is explained by the fact the authors (Berul and Voskresenskaya, 1965; Smirnova et al., 1977) observed that sodium metaphosphate has varieties that may differ in melting point.

Sodium chloride is the most common and non-deficient inorganic salt, which has led to special attention to it. Sodium chloride is a salt of a strong acid, so under normal conditions with orthophosphoric acid, it does not react, which is reliably confirmed by thermodynamic analysis of the following reactions:

$$3NaCl + H_3PO_4 = Na_3PO_4 + 3HCl \uparrow \quad (7)$$

$$2NaCl + H_3PO_4 = Na_2HPO_4 + 2HCl \uparrow \quad (8)$$

$$NaCl + H_3PO_4 = NaH_2PO_4 + HCl \uparrow \quad (9)$$

However, the same thermodynamic analysis showed that when heated above 200°C, the interaction between sodium chloride and orthophosphoric acid becomes possible (Fig. 7). This effect can theoretically be realized for the synthesis of phosphate binders.

The experiment confirmed the assumption about the synthesis of the phosphate binders. The strength of the samples dried at a temperature above 200 °C (Fig. 8), clearly indicates the formation of such binders in the mixture. The mixture samples have the maximum strength at 300 °C.

Differential thermogravimetric analysis of the sample of sodium chloride and orthophosphoric acid after thermal exposure at 300 °C is presented in Fig. 9. The thermogram showed 2 endothermic effects of different intensity. The mass of the sample in the range up to 800 °C practically does not change.

X-ray phase analysis of the same sample showed that binders are sodium trimetaphosphate $(NaPO_3)_3$ (Fig. 10, a). Therefore, in this system does not occur any of the previously analyzed reactions (7)–(9), and the reaction is following:

$$3NaCl + 3H_3PO_4 = Na_3P_3O_9 + 3HCl \uparrow + 3H_2O \uparrow \quad (10)$$

The total formed phosphates are near 30%, other is sodium chloride, which did not react due to insufficient acid.

The formation of sodium trimetaphosphate is explained by the fact

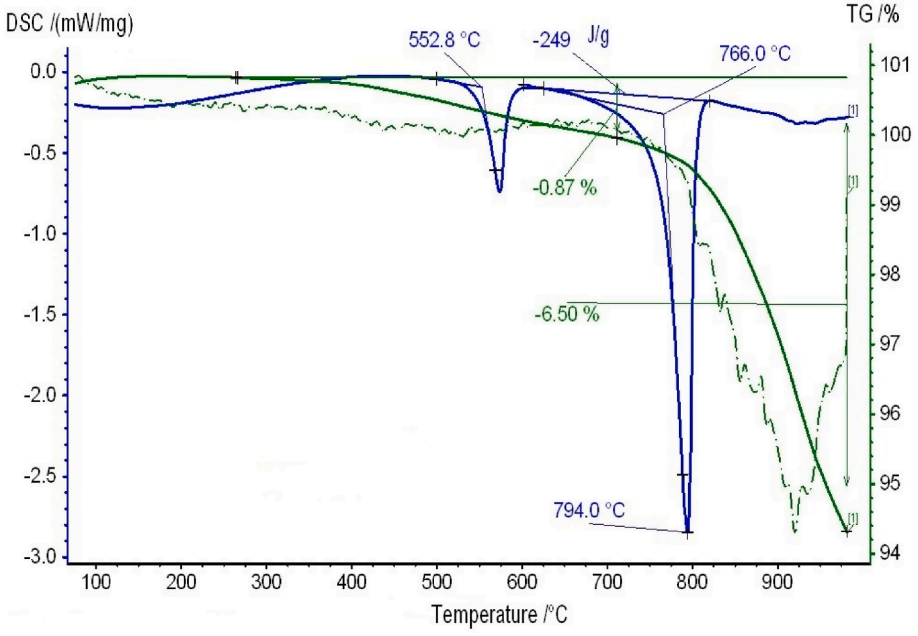

Fig. 9. Differential thermogravimetric analysis for the mixture of sodium chloride (8 mass units) and orthophosphoric acid (3 mass units) after thermal exposure at 300 °C.

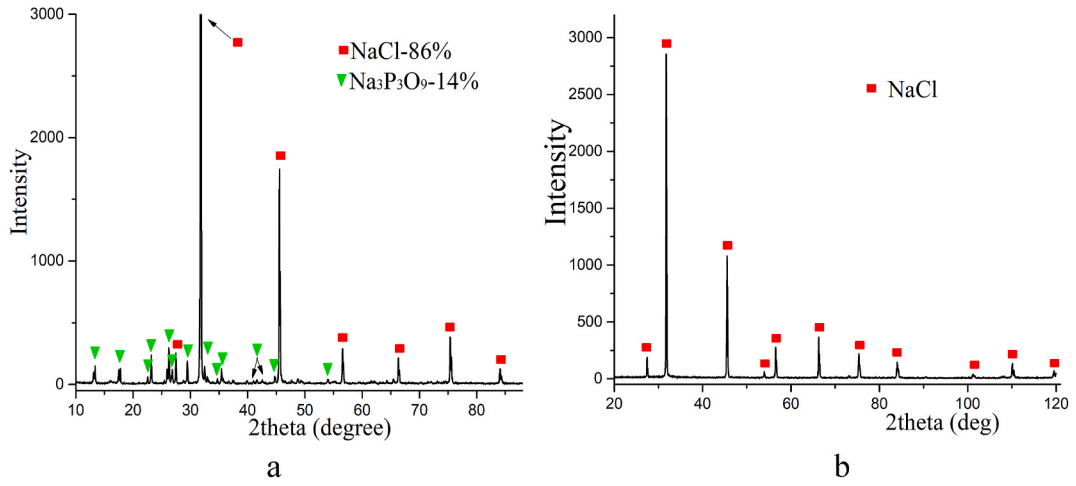

Fig. 10. X-ray phase analysis for the mixture of sodium chloride (8 mass units) and orthophosphoric acid (3 mass units) after thermal exposure at 300 °C (a) and 700 °C (b).

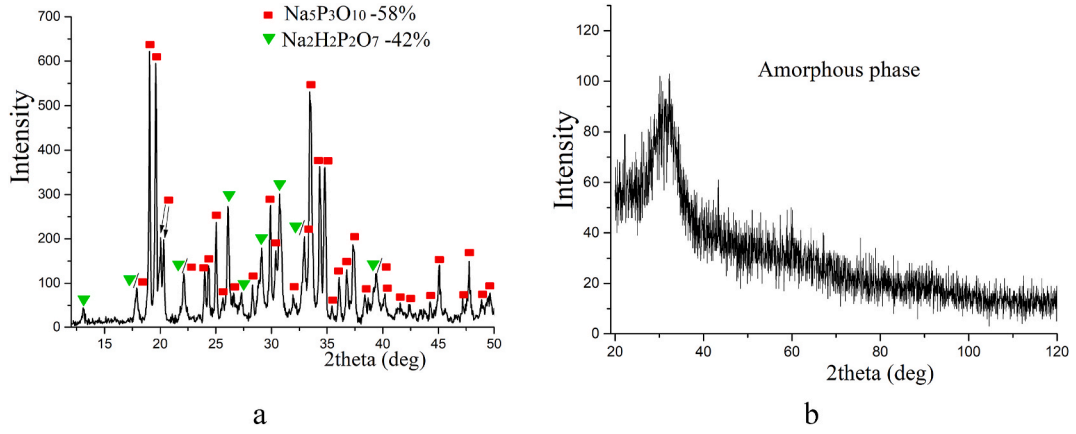

Fig. 11. X-ray analysis of the mixture of sodium tripolyphosphate (5 mass units) and orthophosphoric acid (1 mass units) after thermal exposure at 200 °C (a) and 700 °C (b).

that it occurs in the temperature range of 250 … 300 °C. It is known that at temperature less 215 °C the most stable is orthophosphoric acid H_3PO_4, in the range from 215 to 300 °C it is pyrophosphoric acid $H_4P_2O_7$, and at 300 °C and more it is metaphosphoric acid HPO_3 (Sudakas, 2008). Therefore, the formation of sodium metaphosphate is absolutely logical for the sample after exposure at 300 °C. The form of this metaphosphate is slightly different from that formed in the mixture of sodium carbonate with orthophosphoric acid, but in essence they are salts of related acids, so they must have the same or similar properties.

According to the known phase composition of the experimental mixture, an explanation of the thermal effects during its heating was found. The endothermic effect at 553°C corresponds to the melting of sodium trimetaphosphate, thereafter it turns into an amorphous state. So the phase analysis (Fig. 10, b) of the sample treated at 700°C shows only sodium chloride in the crystalline state. The endothermic effect at 794°C is due to the melting of sodium chloride. In general, the formed binders are thermally stable.

Sodium tripolyphosphate (STPP) is a salt of one of the phosphoric polyacids. This fact determines that it has binding properties. However, it does not provide a sufficiently high level of strength required for the manufacture of molds and cores, so this common, non-scarce and environmentally friendly material is not widely used in foundry technology. The authors (Liutyi et al., 2020) observed the crystal structure and binding potential of sodium tripolyphosphate can be significantly changed after chemical transformation. This transformation occurs when STPP is combined with orthophosphoric acid. Heating of this mixture leads to an interaction between them, which results in the formation of disodium pyrophosphate:

$$2Na_5P_3O_{10} + 4H_3PO_4 \xrightarrow{150\ldots200^oC} 5Na_2H_2P_2O_7 + H_2O \quad (11)$$

The fact of pyrophosphate formation was confirmed by X-ray phase analysis (Fig. 11, a). The difference in the crystal structure of this salt and STPP are, firstly, in the ratio of the ionic radii of sodium and phosphate-ion, and secondly, the two hydrogen atoms present in the molecule pyrophosphate. The ratio of ionic radii in this pyrophosphate is equal to 0,196, according to the calculation. This falls within the recommended range (0,12 … 0,25) to achieve the highest binding potential (Kingery et al., 1976; Sudakas, 2008). Hydrogen atoms provide additional hydrogen bonds, which in turn increase the binding potential.

The obtained material, as shown by phase analysis, consists of approximately equal number of sodium pyrophosphate and STPP. At the same time, it provides an increase in the strength of the core mixture based on quartz filler in 2 … 3 times (Liutyi et al., 2014, 2020). According to reaction (11), an increase in the amount of orthophosphoric acid leads to the increase in the percentage of sodium pyrophosphate in the obtained binder. However, that this greatly complicates the technology of synthesis of binders, so the presented composition (Fig. 11, a) is optimal for the simplicity of the synthesis technology and a high level of properties.

After heating to 700 °C, the binders completely turns into the

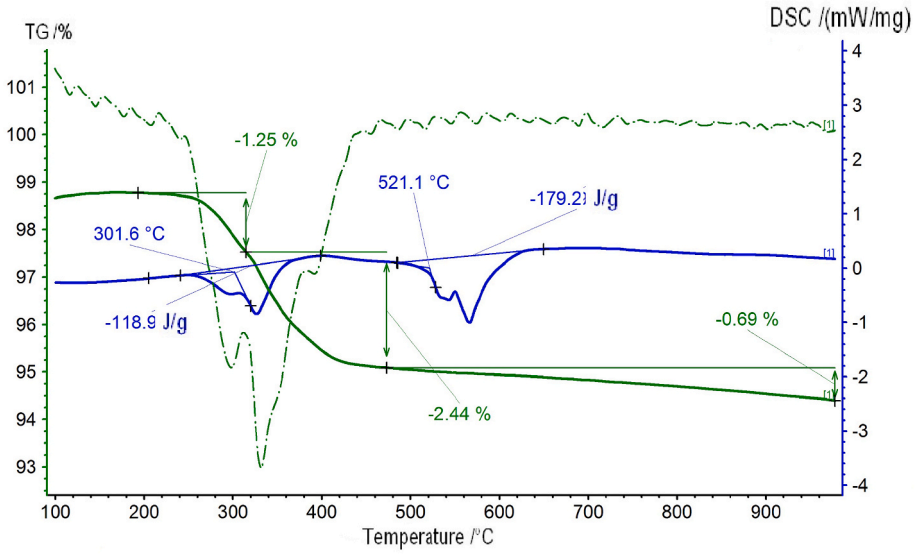

Fig. 12. Differential thermogravimetric analysis for the mixture of sodium tripolyphosphate (5 mass units) and orthophosphoric acid (1 mass unit) after thermal exposure at 200 °C.

amorphous state (Fig. 11, b).

Differential thermogravimetric analysis was performed to establish physical and chemical transformations in this system during its heating. It showed that in general the synthesized binders are characterized by thermal stability (Fig. 12).

Some endothermic effects were found. To analyze and explain it, we used the results of the authors (Lorent and Szeplaki, 1967; Lidin et al., 2000; Berul and Voskresenskaya, 1965; Smirnova et al., 1977), who studied the properties of sodium phosphate when heated.

The beginning of the first endothermic effect is near to 250 °C. According to (Lidin et al., 2000), in the temperature range 220 … 250 °C sodium pyrophosphate turns into metaphosphate by the following reaction:

$$Na_2H_2P_2O_7 \xrightarrow{220\ldots250^oC} 2NaPO_3 + H_2O \quad (12)$$

Calculated according to reaction (12), the weight loss in the form of H_2O vapors is 8.1%. Taking into account the amount of sodium pyrophosphate in the sample (41.8%), the estimated weight loss is 3.4%. According to the thermal analysis curve (Fig. 12), this value is 3.7%, which almost coincides with the theoretical one. Thus, in this system, as in the previous ones, sodium metaphosphate was formed.

The endothermic effect on the thermal analysis curve at temperature of 510 … 530 °C, according to the authors (Illarionov et al., 2012), corresponds to the polymorphic transformation of $Na_5P_3O_{10}$ (II) into $Na_5P_3O_{10}$ (I). We observed the similar endothermic effect at a temperature of 521,1 °C. This explains the amorphous structure of the sample, which was heated to the temperature 700 °C (Fig. 11, b).

The sodium metaphosphate formed by reaction (12) is similar to those metaphosphates we have observed in orthophosphoric acid systems with sodium carbonate and chloride. Therefore, in the temperature range 500 … 600 °C it must melt and turn into the amorphous state. The authors (Berul and Voskresenskaya, 1965; Smirnova et al., 1977) observed the corresponding effect at the temperature near 580 °C according to the thermal analysis curve of $(NaPO_3)_n$. The thermal analysis curve (Fig. 12) shows the double endothermic effect, the first part of which is closer to the temperature of 520 °C, ie polymorphic transformation of STPP, and the second one is near 580 °C, which obviously corresponds to the melting of sodium metaphosphate.

The absence of crystalline phases in the sample after heating and cooling is due to the fact that sodium tripolyphosphate and sodium metaphosphate are completely converted into amorphous state.

3.1. Use of developed materials for casting

Sodium phosphate binders synthesized in our work were used to make foundry cores. According to the results of Figs. 3 and 8, formed by the interaction of inorganic sodium salts with H_3PO_4, phosphates in combination with the refractory filler provide high strength. But for the foundry technology the required properties are also high thermal resistance, low chemical activity to the poured metal, as well as minimal work of extracting cores from cast parts.

The first core mixture consists of quartz sand (95 mass units) and binder (5 mass units). Binder consist of 30 mass units of sodium carbonate and 70 mass units of orthophosphoric acid. To give strength the cores are dried at the temperature of 150 °C.

The second core mixture consists of quartz sand (95 mass units) and binder (5 mass units). Binder consist of 30 mass units of sodium chloride and 70 mass units of orthophosphoric acid. To give strength the cores are dried at the temperature of 300 °C.

The third core mixture includes quartz sand (95 mass units) and binder (5 mass units). Binder consists of 25 mass units of sodium tripolyphosphate and 75 mass units of orthophosphoric acid. To give strength the cores are dried at the temperature of 150 °C.

The research of the chemical stability of the developed core mixtures was carried out by technological samples on formation of the burn (Fig. 1, a). The molds were filled with cast iron, which crystallized by a metastable system, ie with the formation of free cementite. The pouring temperature is 1450 °C. The choice of alloy and temperature is made in order to create the most extreme conditions for the formation of burns.

As a result, it was found that the walls of all castings up to 20 mm thick have absolutely no burns. Walls 30 mm and 40 mm thick have a slight burn. Therefore, the rods from the developed core mixtures can be used without non-stick coatings to obtain thin-walled castings from ferrocarbon alloys.

Surface roughness was determined on the inner and outer sides of the casting wall with the thickness of 20 mm. The inner cavity is formed by core from the studied mixtures, the outer cavity is formed by a traditional sand-clay molding mixture. Cores from the mixture based on H_3PO_4 and sodium carbonate provides the roughness on the R_a scale from 20.1 to 33.4 μm; the mixture based on H_3PO_4 and sodium chloride roughness is from 25.8 to 46.8 μm; the mixture based on H_3PO_4 and sodium tripolyphosphate roughness is from 22.0 to 29.8 μm. On the other (outer) side of the castings, the roughness is in the range of 70 … 120 μm. Therefore, the developed mixtures are able to provide

Fig. 13. Cast iron castings made by founder cores of developed sodium phosphate binders: a) based on H_3PO_4 and Na_2CO_3; b) based on H_3PO_4 and NaCl; c) based on H_3PO_4 and $Na_5P_3O_{10}$.

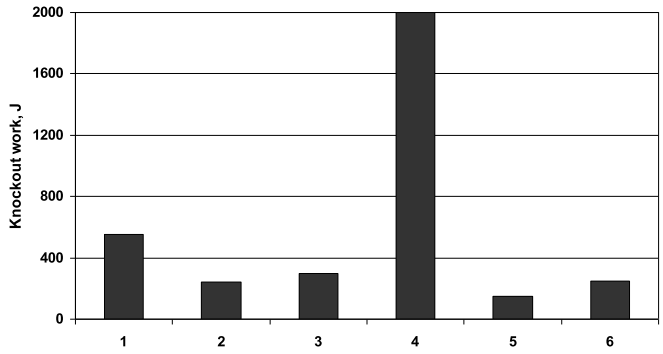

Fig. 14. The knockout work of the casting cores from the internal cavities of the cast iron castings.

satisfactory quality of cast surfaces.

The knockout work of the cores from the castings was determined by the technological sample (Fig. 1, b), which is the prismatic casting with two cores of the diameter of 50 mm. As a result of experimental casting, it was observed that sodium phosphate binders are mainly resistant to physical and chemical interaction with the melt. This is evidenced by the absence of burns on the inner surfaces of the castings (Fig. 13).

It has been experimentally observed that the extraction of cores from castings requires considerable effort (Fig. 14). This is due to the phase transformations of the developed binders when heated. In all cases, it leads to the melting of sodium phosphates in the temperature range 550 … 620°C and subsequent solidification of its melt when cooling. As a result, the cores have the high residual strength. The same is true for mixtures with a well-known liquid glass binder. According to comparative data of the authors (Davidenko et al., 2018; Karateev et al., 2018), the work of knocking out the cores is almost the same as the data we obtained. Fig. 14 shows the knockout work of the casting cores from the internal cavities of the cast iron castings obtained using different binders: 1 - the mixture with orthophosphoric acid and sodium carbonate; 2 - the mixture with orthophosphoric acid and sodium chloride; 3 - the mixture with orthophosphoric acid and sodium tripolyphosphate; 4 - the mixture with liquid glass; 5 - the mixture with liquid glass and hardener furfuryloxypropyl cyclocarbonate; 6 - the mixture with liquid glass and traditional ester hardener (from 1 to 3 are our results, from 4 to 6 are the authors (Davidenko et al., 2018; Karateev et al., 2018)).

However, sodium phosphates are water-soluble, unlike other low-melting binders used in foundry technologies. It is observed that after immersion of the cast part with the core in cold water, the core is easily extracted after 30 … 60 min without any mechanical knockout.

4. Conclusions

1. As a result of theoretical and experimental investigation, for the first time the phosphate binders was obtained due to the chemical interaction of orthophosphoric acid and sodium chloride, what is the salt of the stronger hydrochloric acid. It is confirmed that stable phosphate binders are formed by synthesis at the temperature 300 °C and more.
2. Mutual transformations of sodium phosphates, including polymeric ones, are analyzed, and the synthesis technology of phosphate binders with increased physical and mechanical characteristics due to interaction of orthophosphoric acid and sodium tripolyphosphate is developed.
3. It was determined that regardless of the source materials (sodium carbonate, chloride or tripolyphosphate), which are used for the synthesis of phosphate binders, when heated these binders behave similarly. In the temperature range 200 … 300 °C all three researched systems turn into sodium metaphosphates of different types with the general formula $(NaPO_3)_n$, and after heating to 600 … 700 °C the amorphous state is formed.
4. All researched sodium phosphates have a set of functional properties required for the manufacture of foundry molds and cores: high strength in combination with refractory filler, sufficient thermal stability, easy extraction of castings from molds and cores due to the water-soluble of sodium phosphates.
5. As a result of experimental verification of the developed materials and core mixtures, these binders provide the proper quality of cast surfaces of parts made of ferrocarbon alloys is shown. At the same time any surface defects are absent that confirms suitability of the developed materials for use in foundry production.

Declaration of interest

The authors R. Liutyi, I. Petryk, M. Tyshkovets, O. Myslyvchenko, D. Liuta, M. Fyodorov declare that there is no conflict of interests regarding the publication of the manuscript "**Investigating sodium phosphate binders for foundry production**".

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