

# Eco-friendly hybrid binders based on waste from the chemical industry

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**Abstract.** The purpose of the study is to show the possibility of using high-tonnage waste from the chemical industry in the production of building materials. **Methods and materials.** Methods of data comparison and analysis were used. Solid residues of distiller sludge with a moisture content of 25-30%, an active calcium oxide content of 12-13% and quartz sand with a grain size of 2.2, humidity of 5-6% were used as materials. **Results.** Compositions and methods for obtaining a cement-free binder based on the solid residue of soda and quartz sand production are proposed. The possibility of obtaining a binder based on the solid residue of distiller slurries according to two technological schemes: drying of the solid residue and grinding together with quartz sand; firing of the solid residue and grinding together with quartz sand, has been confirmed by our tests. The introduced concept of "Eco-friendly hybrid cements" (Eco-friendly hybrid binders (EHB)) emphasizes that they are binders made up of multicomponent mineral raw materials of secondary resources. **Practical significance.** Solid by-products of the chemical industry can be used as an auxiliary inorganic component. This will make it possible to create eco-friendly hybrid cements ready for use, which are sealed only with water, which contributes to the development of such binders by industry and the rational use of secondary mineral resources.

## 1 Introduction

The construction of residential and industrial buildings acquired significant proportions at the beginning of the 20th century. This has happened in both urban and rural environments. The large volume of construction necessitates the introduction of new progressive materials. These materials provide an opportunity to intensify the construction industry, reduce its labor intensity and cost, and reduce the own weight of buildings under construction.

The expansion of the production of wall and finishing products based on local natural raw materials is an important issue of increasing the efficiency of this industry. Cement, lime, quartz sand, crushed stone and gravel-sand mixture are the traditional raw materials for them. The experience of replacing Portland cement with other binders has been accumulated in many countries. The use of binders from man-made raw materials changes the technological cycle, for example, excludes roasting. This leads to a significant reduction in the cost of production.

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The relevance of the chosen topic lies in the fact that the recycling of waste and by-products of industry, including metallurgical, chemical and mining, is acute in Russia

Active research is currently underway to develop new formulations of low-clinker binders based on secondary resources that meet the requirements of the EN 197-1 standard [1-4]. Research is also underway to develop new CEM III/C cement formulations. These compositions may contain blast furnace (converter) or electric steelmaking slags in the amount of 81-95%, Portland cement clinker 5-19%, and an auxiliary inorganic component of 0-5%. An organic component can also be used.

The compositions of these cements have not been sufficiently developed, and the durability of concrete from them has been poorly studied in Russia. Such cements are produced in limited quantities.

A large volume of man-made raw materials is not disposed of properly in Russia [5,6]. This applies to granular, dump slag from the metallurgical industry and ash slag from thermal power plants, waste from chemical industries.

The experience of foreign partners and the results of Russian scientists [7-12] will allow us to develop new binders for durable cement composites. Methods for evaluating the properties of these composites are being improved in assessing the durability of artificial stone. The study of the properties of stone in the aspect of durability will expand the scope of application of binders based on industrial waste in transport, industrial and underground construction [13,14].

Waste from the production of clinker, pozzolans, deposits, silica, fly ash, burnt shale, limestone, calcium sulfate (natural and secondary) can be used as an auxiliary inorganic component. There may be inorganic natural mineral additives, including combinations of these components [15].

Regulatory documents do not give specific instructions on the compositions of cements with a high content of CEM III/C slag. This requires comprehensive research on the use of secondary resources to produce hybrid binders with improved properties.

The study of the nature and mechanism of hardening of environmentally friendly hybrid cements based on blast furnace (converter) or electrothermophosphoric slags requires justification for the use of natural and secondary resources and their combinations as an auxiliary inorganic component, as technological additives – organic or inorganic components in order to determine the optimal conditions for controlled phase and structure formation for durable cement composites.

The possibility of using certain secondary resources of the Republic of Bashkortostan will be considered in this work. Millions of tons of crushed limestone mass of the former Shakhtau mountain are laid at the bottom of the so-called "white sea".

This is the waste of Bashkir Soda Company JSC. They can be widely used as the main raw material component for the production of cement-free binders and various wall and masonry products. The works of many scientists in the field of building materials science are devoted to this issue [6,9].

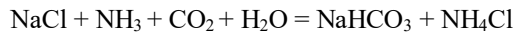
There is already experience in the use of ash and slag and waste from mining for land reclamation and liming of acidic soils, as well as backfilling of mine workings and ravines, construction of road foundations and sports facilities. Pilot batches were also obtained for a number of items of the nomenclature of construction products made with binders from production waste. Today, such waste is not used properly, although in Bashkiria alone, their amount is several tens of millions of tons.

The possibility of using, first of all, lime-containing waste, for example, in hybrid binders, will improve the environmental situation in the region. The concept of "hybrid binders" was introduced in the XXI century, and it is the development of the theory and practice of such materials that the authors plan to pay further attention to, taking into account the multi-tonnage waste of various industries in their compositions.

A common industrial method for the production of soda ash is currently ammonia, based on liquid–gas chemisorption processes. Limestone, table salt (in the form of saturated brine) and ammonia are the raw materials for the production of soda.

The principle of obtaining soda by the ammonia method is described below. A solution of table salt or a natural brine is purified from impurities of calcium and magnesium salts by precipitation. The brine passes through absorption columns, where it is saturated with ammonia and carbon dioxide and sodium bicarbonate is formed as a precipitate.

The total reaction of this process has the following form:



Sodium bicarbonate precipitated undergoes filtration and calcination. Soda ash is formed after.

The sludge is clarified in the "white seas" by sedimentation. Solid phase particles accumulate in pools during coagulation. Clarified liquid containing soluble chloride salts of calcium, sodium and ammonia is partially drained into reservoirs. Some of it is pumped into oil reservoirs to maintain reservoir pressure.

The conducted research on the use of industrial waste of various origins will allow in the near future organizing the closed technological cycles of waste-free and low-waste production in the production of a certain range of building materials. This will improve the air and water basins of the republic.

## 2 Materials and methods of research

The solid residue of distiller slurries is a dispersed mass of light gray color. It is used for the manufacture of building materials. It consists in dry form mainly (70-80%) of particles with a size of 0.1- 0.2 mm, bulk – 970 kg/m<sup>3</sup>, density – 2.22 g/cm<sup>3</sup>.

The solid residue consists of calcium carbonate (on average 63%), calcium hydroxide (11%), impurities of clay minerals and chloride salts. The chemical composition of the solid residue as a whole varies within small limits. There are significant fluctuations in the content of calcium chloride. Calcium carbonate is 10-12%. It is the main element.

The chemical and phase composition of the solid residue gives the solid a significant difference from known natural materials. The solid residue of distiller slurries contains a number of oxides in its composition. These oxides are an integral part of compounds of silicate systems (hydrosilicates, hydroaluminates, hydrogranates) with astringent properties.

In this regard, a technology has been developed for the production of binders based on the solid residue of distiller slurries. The optimal composition of the raw material mixture has been selected, which has astringent properties under hydrothermal hardening conditions.

The development of the binder composition is based on modern ideas about the physico-chemical processes of synthesizing the strength of silicate systems at elevated temperatures. The main attention was paid to the selection of such compositions of the raw material mixture and technological techniques that cause the formation of calcium hydrosilicates in the hardening products. The content of silicon oxide in the solid residue is small. Quartz sand was used with a silicon oxide content of 86.3 – 88.2% (Table. 1), It was used as a silica component.

## 3 Results

The basic technological scheme for obtaining a binder is as follows. The solid residue of the distiller sludge, selected from the sludge accumulator, is dried and then co-ground in a ball mill with quartz sand. The technology for producing a distiller-silica binder based on an

unburned solid residue differs from that described in that the firing and cooling stages are excluded from the technological process, and gypsum stone is not added during grinding. The resulting product is a clinker-free autoclave-hardening binder with a rather complex chemical composition.

**Table 1.** Chemical composition (%) of raw materials used for the manufacture of binder

Materials	Ca	SiO <sub>2</sub>	MgO	Al <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub> -	Cl -	CaO <sub>act</sub>	Others
Sand								
Before drying	1.20	86.3	1.05	5.02	-	-	-	3.82
After drying	1.40	88.16	1.16	5.76	-	-	-	1.22
Solid residue								
Before drying	28.22	5.69	1.78	0.64	1.70	3.65	12.00 - 14.00	35.02
After drying	49.01	6.52	2.94	1.02	1.49	3.42	12.00 - 14.00	32.65

The chemical composition of the experimental samples of binders made on the basis of the solid residue of the production of soda and quartz sand is shown in Table 2

**Table 2.** Chemical composition of binders made on the basis of solid residue of soda and quartz sand production (%)

Sample	CaO / SiO <sub>2</sub>	CaO <sub>act</sub>	CaO <sub>tot</sub>	MgO <sub>tot</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	SO <sub>3</sub> -	Cl -	Others	Note
1	0.60	25.15	30.60	3.52	44.55	6.01	2.35	2.49	1.53	9.33	On the burnt solid residue
2	0.51	21.81	32.87	3.79	45.28	6.05	3.31	1.68	0.89	6.63	
3	0.46	19.18	32.02	2.98	44.04	5.41	2.53	1.89	1.05	9.58	
4	0.19	7.30	24.85	2.68	41.35	4.62	1.96	7.57	2.00	14.77	On the non- burnt solid residue

The proposed method for obtaining a cement-free binder based on the solid residue of soda and quartz sand production is quite effective for technological and economic reasons. But it is worth considering the following. The cement-free binder has two significant drawbacks. The binder has a relatively low strength due to the low activity of the initial solid residue (12-14%); secondly, the instability of the mineralogical chemical composition of the solid residue makes it difficult to optimize the composition of the binder, which does not provide stable strength indicators.

These disadvantages can be eliminated by firing. The following has been established as a result of experiments. The final strength of the hardened stone obtained from the calcined (at a temperature of 800-1050 °C) solid residue and quartz sand reaches the order of 100MPa, corresponding to the grade of binder 500.

It is known that the marketable properties of binders (activity, strength, durability, etc.) are determined by a variety of technological factors in their manufacture. These are the activity of the initial components, their phase composition and their ratio in the raw material mixture, autoclave hardening conditions, specific surface area, etc.

Changes in the activity and strength properties of experimental binder samples obtained depending on the conditions of preliminary preparation of solid residue and quartz sand (roasting, grinding, phase composition, ratio of initial components in the raw mixture, etc.) have been studied. The main results of the research conducted by the authors are shown in Tables 3 and 4.

**Table 3.** Change in the activity and strength of the binder depending on the ratio (%) of solid residue and sand in the raw material mass

Sample	Solid residue	Ground residue	Mass activity (%)	Compressive strength (MPa)
1	20	80	5.7	25.9
2	30	70	11.8	42.3
3	35	65	14.1	54.2
4	40	60	15.7	48.2
5	45	55	16.5	42.0
6	50	50	19.6	26.5
7	60	40	23.0	30.0

Tests of the manufacturability of the binder manufacturing process using the solid residue of distiller sludge were carried out in production conditions on equipment temporarily adapted for this purpose.

**Table 4.** Strength properties of the binder obtained on the basis of the burnt solid residue

Sample	CaO <sub>act</sub> , %	CaO/SiO <sub>2</sub>	Sump flow, mm	W/C	Strength, MPa	
					Compressive	Binding
1	25.2	0.59	110	0.44	34.1	6.55
2	25.2	0.59	109	0.448	34.7	6.64
3	25.2	0.59	106	0.443	32.7	5.90
4	23.6	0.58	110	0.49	35.7	5.90
5	22.1	0.57	105	0.45	39.8	6.75
6	22.1	0.57	106	0.47	35.0	7.40
7	22.1	0.57	110	0.49	40.0	7.30
8	19.8	0.46	110	0.48	60.8	8.76
9	19.8	0.46	108	0.428	54.9	8.34
10	17.63	0.42	108	0.42	60.3	8.58
11	17.63	0.42	112	0.55	51.1	9.60
12	17.87	0.425	106	0.428	66.3	7.90
13	17.87	0.425	108	0.435	67.7	7.85
14	17.87	0.425	110	0.44	68.6	7.88

Quartz sand with a grain size of 2.2, a humidity of 5-6%, containing 86-91% silicon oxide and a solid residue from the sludge accumulator of the "white sea" with a humidity of 25-30% and an active calcium oxide content of 12-13% were used as a raw component.

Production tests were carried out according to two schemes: without firing and with firing.

Sand and solid residue were loaded by a grab crane into a consumable hopper, from which, using an autoclave dispenser and a belt conveyor system, materials were sent to a rotating furnace designed for firing barite ore (length - 35 m, diameter – 8 m, tilt angle - 2),

where, depending on the required conditions, a certain thermal regime was created. Heat treatment (drying and roasting) of raw materials was carried out on the same production line.

Drying of sand and solid residue was carried out at a temperature of 400-600°C, and roasting at a temperature of 800-950°C.

The dried or burnt solid residue was discharged from the furnace to the storage site using a scraper conveyor.

The control over the technological process of drying and firing is carried out as follows. Materials were selected before and after heat treatment every hour. The indicators were determined in the selected samples as follows. Humidity and granulometric composition – in the sand; humidity and content of active calcium oxide – in the solid residue; content of active calcium oxide, duration and quenching temperature - in the solid residue firing product. The average exchange samples were compiled from selected samples of materials and subjected to chemical analysis.

The solid residue used to produce the binder according to the first scheme was characterized by an active calcium oxide content of 12% on average and a moisture content of 24%. Moisture was absent both in the solid residue and in the sand after drying.

The binder obtained according to the first scheme meets the requirements for autoclave binders according to the main indicators. It has a low content of  $\text{CaO}_{\text{act}}$ , so the strength of this binder barely reaches the 200 mark.

This disadvantage is eliminated by applying the second scheme of binder production. The second scheme includes the operation of increasing the activity of the solid residue by firing. Therefore, the second scheme is of the greatest interest. In this variant, the main attention was paid to the study of the technological parameters for obtaining a binder based on a burnt solid residue.

Sand containing an average of 88%  $\text{SiO}_2$ , of medium size, with a humidity of 5-6% and a solid residue with an average humidity of 30% is used to obtain a binder according to the second scheme.

The optimal firing mode of the solid residue was adopted such that the content of active calcium oxide in the burnt product was at least 40%, and the duration of quenching was no more than 20 minutes.

The clogging occurred when the furnace was loaded during the firing and drying process. This led to uneven loading. The temperature regime varied depending on the amount of incoming material. As a result, the content of  $\text{CaO}_{\text{act}}$  in the firing product ranged from 33 to 61% (on average 52.3%), and the duration of quenching ranged from 1.5 to 15 minutes.

The burnt solid residue from the furnace heat was discharged by an inclined scraper conveyor outside the workshop and stored in an open area.

The prepared binder components (firing product and dry sand) were previously ground in a ball mill and fed in the process in a predetermined ratio. The process of obtaining the binder mainly corresponded to the specified parameters, in particular, in terms of the content of active compounds of  $\text{CaO}_{\text{act}}$  in the initial raw materials. The average productivity of the mill was 11 tons/hour with these indicators of fineness of grinding. The technical characteristics of the distiller-silica binder are presented in Table 5.

**Table 5.** Technical characteristics of distiller-silica binder

Bulk weight	980 kg/m <sup>3</sup>
Density	2620 kg/m <sup>3</sup>
Specific surface area	5130 cm <sup>2</sup> /g
The remainder on the sieve No. 008	6.8 %
Vicat's consistency of paste	32 %
The beginning of the setting	12 min
The end of the setting	20 min

## 4 Discussion

The distiller-silica binder meets the requirements for its basic parameters for autoclave binders made from traditional raw materials. Strength indicators vary within relatively wide limits. The maximum compressive strength of the binder in a sand solution of the composition is 1:3 (binder: normal sand) is 68.6 MPa, and the minimum is 34.1 MPa (see Table 4).

Obtaining a binder with the desired properties is to ensure stable activity of the burnt solid residue by creating a constant firing mode. The latter indicator depends on the uniformity of the furnace load. This is achieved if the solid residue entering the furnace is pre-dried, for example, in a drying drum.

The setting time of the resulting binder is too short: the beginning of setting is 10-12 minutes, the end is 16-25 minutes. This can cause difficulties when forming products in production conditions. The setting time can be extended if gypsum (2-3%) is added during grinding, as well as when obtaining lime-silica binders.

The change in the setting time of the distiller-silica binder depends on the moisture content. The contact of moisture even from the air leads to the fact that there is a quenching of calcium oxide and a lumping of the binder mass. Therefore, the distiller-silica binder, like all materials prepared on the basis of lime, should be stored in hermetically sealed containers.

The technology for producing a distiller-silica binder using soda production waste is as follows.

The initial solid residue (with a moisture content of 25-33%) from the sludge accumulators is extracted by an excavator and stored in bunks, then transported to a raw material warehouse. After that, the sludge accumulator undergoes preliminary preparation in a two-shaft mixer, in order to reduce humidity, it is mixed with the dried solid residue. The prepared raw material mass with a humidity of about 20% is fed for granulation into perforated rollers.

The finished granules at the outlet are powdered with solid residue dust, which is captured during the purification of exhaust gases, and sent to the drying drum. The dried granules are fed into a rotating shaft furnace, where roasting takes place at a temperature of 800 – 900 °C. During firing, the time and temperature are adjusted taking into account the activity of the burnt solid residue (the activity of the residue should be at least 45-50%, duration – no more than 20 minutes).

The burnt solid residue is transported to the discharge hopper after cooling and enters the ball mill through a weighing dispenser. Quartz sand (pre-sifted and dried) and gypsum stone are fed there according to the prescribed dosage. The components are ground to a specific surface area of 3000 – 5000 cm<sup>2</sup>/g, depending on the required grade of binder. The finished binder is supplied to the silos by pneumatic transport.

The technology for producing a distiller-silica binder based on an unburned solid residue differs from that described in that the firing and cooling stages are excluded from the technological process, and gypsum stone is not added during grinding.

The production of binder is more economical according to the "drying-grinding" scheme than according to the "roasting – grinding" scheme. The dried solid residue with an activity of at least 12% is used as a calcium-containing component. However, the resulting binder has relatively low strength characteristics (corresponding to grades 200 – 230) in the first case. The strength of the binder obtained by the firing scheme is 2.5 – 3 times higher. A solid residue with any activity is suitable for the production of a binder using firing.

The solid residue of distillers in the dumps, due to its chemical composition, being finely ground together with quartz sand, exhibits cementing properties during autoclave treatment. This circumstance is the basis for the development of a technology for obtaining a binder according to a "non-burning" scheme.

The solid residue (content of at least 19% of active calcium and magnesium oxides) is dried at a temperature of 200-300 °C to a residual humidity (W) of no more than 1%, followed by grinding together with dry ( $W \leq 1\%$ ) quartz sand (at certain ratios) to a specific surface area of the binder 3000 – 5000 cm<sup>2</sup> /G.

An increase in the activity of the solid residue by 4-5 times occurs as a result of decarbonization of calcium carbonate at a temperature of 800 – 900 °C. This fact predetermined the development of a technology for obtaining a binder according to the "firing" scheme, which differs from the first ("non-firing") only by the type of heat treatment of the solid residue.

Thus, the already completed complex of laboratory and technological tests with varying the main technological parameters (the ratio of components depending on the activity of the solid residue, the fineness of their grinding, temperature and duration of hydrothermal treatment) within the limits practically feasible in industrial conditions showed that the solid residue of distiller sludge is a suitable raw material for the manufacture of cement-free binder.

The possibility of obtaining a binder based on the solid residue of distiller slurries according to two technological schemes: drying of the solid residue and grinding together with quartz sand; firing of the solid residue and grinding together with quartz sand, has been confirmed by our tests.

The main technological parameters for the production of a distiller-silica binder have been determined and a schematic diagram of its production has been developed. Binder samples made on the basis of the studied solid waste from soda production and quartz sand are characterized by different grades (from 200 to 600) depending on the technology of their manufacture.

If autoclaves are used, the technology of manufacturing binders does not allow the use of solid residue in soda production on a large scale. Hydrothermal treatment at atmospheric pressure of binder compositions based on solid residue requires pre-firing it together with a silica component (for example, quartz sand) at a temperature of about 900-1100°C. The resulting firing products contain a belite phase, which accelerates the hardening process of the mass even without autoclaving. The transition to lime-belite binder technology will significantly reduce the specific cost of fuel, electricity and reduce the cost of production.

## 5 Conclusion

The authors of the paper introduce the concept of "Eco-friendly hybrid cements" (EHB) based on the above to emphasize that they consist entirely of multicomponent mineral raw materials of secondary resources. Strengthening the action of individual binder components will allow you to control the phase and structure formation of cement stone to obtain durable compositions.

The nature and mechanism of hardening of multicomponent hybrid cements to obtain durable cement matrices have been little studied, which makes it difficult to predict the phase and structure formation of cement stone, and, consequently, its properties that determine durability.

The authors propose a concept for the production of environmentally friendly hybrid cements for durable cement matrices. The concept consists in the directional control of the reactivity of the binder and the structural uniformity of the solid phase during one-component mixing of the binder with water. At the same time, it is necessary to scientifically substantiate the choice of components in eco-friendly hybrid binders as a result of establishing correlations between the composition, structure and physico-mechanical properties of the cement matrix. The results of the study of hydration products of eco-friendly hybrid binders, taking into account the influence of physico-chemical factors of influence on the phase and structure formation of hardening compositions, will allow us to propose a technology for the

manufacture of new building materials based on these binders. The new research results obtained will contribute to the development of such binders by the industry and the rational use of secondary mineral resources.

### References

1. Smirnova, O. M., *Journal of Materials in Civil Engineering*, **32(7)**, 06020008. (2020). [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0003241](https://doi.org/10.1061/(ASCE)MT.1943-5533.0003241)
2. Singh, S. K., Singh, A., Singh, B., & Vashistha, P., *Journal of cleaner production* **264**, 121570 (2020) <https://doi.org/10.1016/j.jclepro.2020.121570>
3. Garcia-Lodeiro, I., Fernández-Jimenez, A., & Palomo, A., *Journal of Sustainable Cement-Based Materials* **4(2)**, 140-151 (2015) <https://doi.org/10.1080/21650373.2015.1040865>
4. Kazanskaya, L. F., Smirnova, O. M., Palomo, Á., Menendez Pidal, I., Romana, M. *Materials* **14(2)**, 403 (2021) <https://doi.org/10.3390/ma14020403>
5. Soloviova, V. Ya., Stepanova, I.V. *Transportation Research Procedia* **68**, 237-243 (2022) <https://doi.org/10.1016/j.trpro.2023.02.032>
6. Soloviova, V., Stepanova, I. *Lecture Notes in Networks and Systems (LNNS)* **402**, 898-905 (2022) [https://doi.org/10.1007/978-3-030-96380-4\\_98](https://doi.org/10.1007/978-3-030-96380-4_98)
7. Teng Yi, Shuenn-Ren Liou, Wen-Yih Kuo, *Case Studies in Construction Materials*, **18** (2023) e02116 <https://doi.org/10.1016/j.cscm.2023.e02116>
8. Kazanskaya, L. F., & Al-Atasi, N. M. *Lecture Notes in Networks and Systems, 2023*, **575 LNNS**, pp. 2765–2773 (2022) [https://doi.org/10.1007/978-3-031-21219-2\\_309](https://doi.org/10.1007/978-3-031-21219-2_309)
9. Kharitonov, A., Korobkova, M., & Smirnova, O. *Procedia Engineering* **108**, 239-244. (2015) <https://doi.org/10.1016/j.proeng.2015.06.143>
10. Nedoseko I.V., Ryazanov A.N., Ryazanova V.A., Vinnichenko V.I., *Heat Engineering Problems of Phosphogypsum Utilization During Its Processing into Construct mmcion Gypsum. In: IOP Conference Series: Materials Science and Engineering*. International Conference on Civil, Architectural and Environmental Sciences and Technologies (CAEST 2019), **0402-2197**, p. 012119. (2022) <https://doi.org/10.1088/1757-899X/775/1/012119>
11. Riazanov A.A., Riazanov A.N., Nedoseko I.V., Vinnichenko V.I., Rakhimov R.Z. *IOP Conference Series: Materials Science and Engineering. Ser. "Innovative Technology in Architecture and Design, ITAD 2020"*, 012-034 (2020). <https://doi.org/10.1088/1757-899X/907/1/012034>
12. Svatovskaya, L.B., Sychova, A.M., Soloviova, V.Y., Maslennikova, L.L., Sychov, M.M., *Indian Journal of Science and Technology (IJST)* **9(42)**, 104-231 (2016). <https://doi.org/10.17485/ijst/2016/v9i42/104231>
13. Abdullah M.A.H., Rashid R.S.M., Amran M., Hejazii F., Azreen N.M., Fediuk R., Voo Ye.L., Vatin N.I., Idris M.I., *Polymers* **14(14)**, 28-30 (2022) <https://doi.org/10.3390/polym14142830>
14. Thanon Bualuang, Peerapong Jitangiam, Teewara Suwan, Ubolluk Rattanasak, Napat Jakrawatana, Nanticha Kalapat, Hamid Nikraz, *Journal of Materials Research and Technology* **14**, 374-391 (2021) <https://doi.org/10.1016/j.jmrt.2021.06.060>
15. Gu, X., Tan, H., He, X., Smirnova, O., Zhang, J., & Luo, Z., *Materials* **13(20)**, 4526. (2020) <https://doi.org/10.3390/ma13204526>