PHYSICS AND CHEMISTRY OF SOLID STATE
V. 25, No. 3 (2024) pp. 626-638

Section: Physics

DOI: 10.15330/pcss.25.3.626-638

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ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 25, № 3 (2024) С. 626-638

Фізико-математичні науки

PACS: 36.20.Ey; 36.20.-r

ISSN 1729-4428 (Print)
ISSN 2309-8589 (Online)

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Geopolymer for medical application: a review

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The materials for medical application are normally consisted of metal, ceramic, and polymer. Each material has its own limitations such as corrosion in metal, the brittleness of ceramic, and the high temperature problem of polymer. To eliminate their weakness, combining one or more respective materials are encouraged, which termed as composite. One of the emerging composite materials that can be utilized in medical application are geopolymer, which is an inorganic polymer material consisted of aluminosilicate sources such as metakaolin and sol-gel synthesized material and alkali activator consisted of strong alkali hydroxide and sodium silicate solution. This review paper elaborated the raw materials, alkali activators, and admixture for geopolymer, and the application of geopolymer-based material for medical purposes. We also discuss the prospective and challenges of geopolymer for the medical field. The adjustable strength and porosity make this material versatile for coating substrates to become bone scaffold material. However, the concern remains about the leaching and high alkalinity of geopolymers. This could be improved by reducing the molarity of sodium hydroxide and mixing geopolymer with compounds to trap the harmful leachate agent inside and studying different solutions for the activation of geopolymer.

Keywords: antibacterial; bioceramics; drug delivery; geopolymer; medical.

Received 14 May 2024; Accepted 27 August 2024.

Introduction

Geopolymer is an aluminosilicate-based amorphous material that has been used to solve the problem of by-product materials, such as industrial, metallurgical, and agricultural wastes, by alkalization. Furthermore, natural sources that are rich in silicon (Si) and aluminum (Al) can also be used as geopolymer precursors. The aluminosilicate precursor powder reacts with an activating alkaline solution of sodium and/or potassium hydroxides and silicates at temperatures below 100 °C to produce a ceramic amorphous matrix. Currently, geopolymers have been widely used for scientific and industrial applications [1]. These applications include cement and concrete, ceramics, refractory materials, soil stabilizers, coatings, heavy metal removal, pigments, and carbon capture. Portland-cement-based concrete has several issues, such as low alkali-silica reaction (ASR) resistance, is susceptible to corrosion in marine environments, and generates carbon dioxide emissions from the manufacture and transportation of Portland cement [2]. There are also major concerns about stockpiled and unutilized waste material from industries, which can be harmful when directly exposed to the environment. These problems can be solved by geopolymer.

Geopolymer has considerable chemical, physical, mechanical, and morphological characteristics when it made into nanocomposite, which can be applied in the medical field. The factors that hinder the development of geopolymer-based medical applications are their low biocompatibility, which can be solved by the addition of materials that can increase the aforementioned properties. This is reflected in the increased interest in geopolymers for biomaterials application research in recent years. Although geopolymers had been found since 1979 by Davidovits, these inorganic polymers are still a hot topic discussed these years [3]. These are reflected by the increasing number scientific study in terms of geopolymer publications collected from Scopus website as illustrated in Fig.1. The last ten years of Scopus data from 10.633 scholarly papers, showed that the focus on geopolymer research has been dominated by the theme of materials structure and geopolymer concrete, as well as mapping the geopolymer co-occurrence keyword using VosViewer in Fig. **2**. There are still many areas that need to be looked into and strengthened in this regard: (i) the investigation of potential methods to reduce the high alkalinity possessed by geopolymers, which severely restricts biocompatibility; (ii) the careful selection and characterization of aluminosilicate precursors due to the potential presence of heavy metals that could cause severe damage to health; (iii) the study of the stoichiometry of the geopolymerization reaction to find the correlation between the Si/Al ratio and biocompatibility with the cell-level environment.

Data calculation from Biblioshiny analysis shows annual growth rate scholarly paper about geopolymer for medical application circa 5.48% with average citation per document 11.26. Nevertheless, the discussion of geopolymer for medical applications is a new discussion and there are still very few, it doesn't even appear on the yellowish topic map above, so there are still many interesting gaps that can be further studied. Scopus collected only 37 documents related to the keywords geopolymers and medical with a time span from 2010 until 2024 which we can further analyze blibiometrically in Fig. **3**, Fig. **4** and Table 3.

Chemical composition of biomedical waste ash by various researchers. shown the country productivity based on the number of authors, with most of them comes from Asian and European continents.

This paper assesses the potential of geopolymer materials in biomedical applications by examining the findings of published research articles and contrasting them with the characteristics of the materials typically used as antibacterial, drug delivery, implants, and dental materials while emphasizing the advantages and disadvantages. The most recent advancements in materials made of geopolymers that could be used in the biomedical sector are covered in this review and

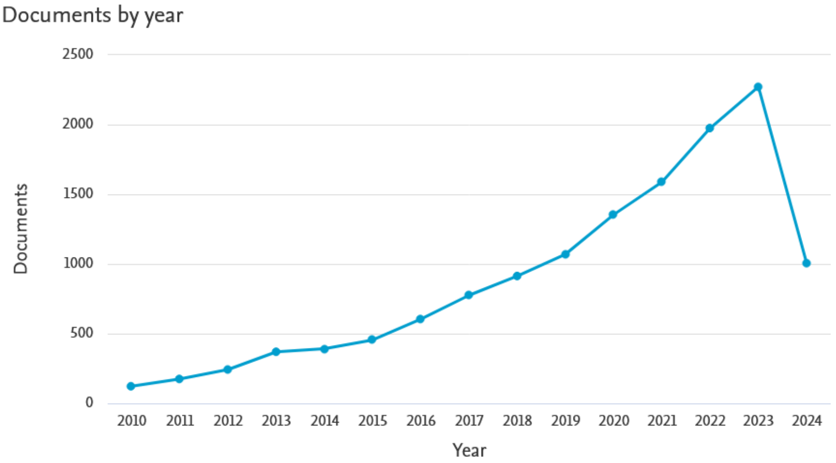


Fig.1. The number of research publications of geopolymer from Scopus by year per May 2024.

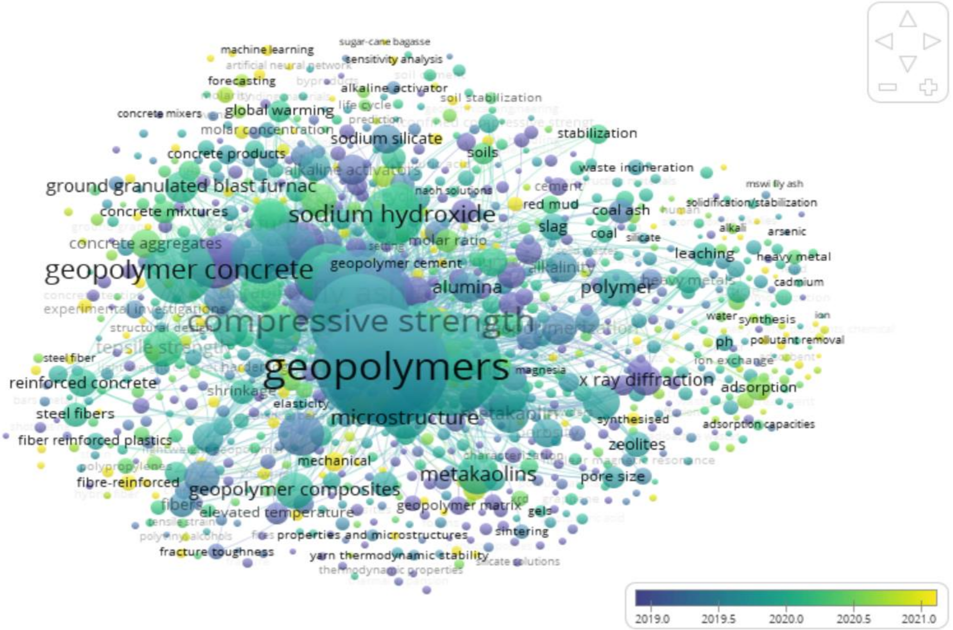


Fig. 2. (a) Clustering topic geopolymer from scholarly papers Scopus data, (b) overlay visualization based on the average occurrence of keywords by year based on Mapping VosViewer.

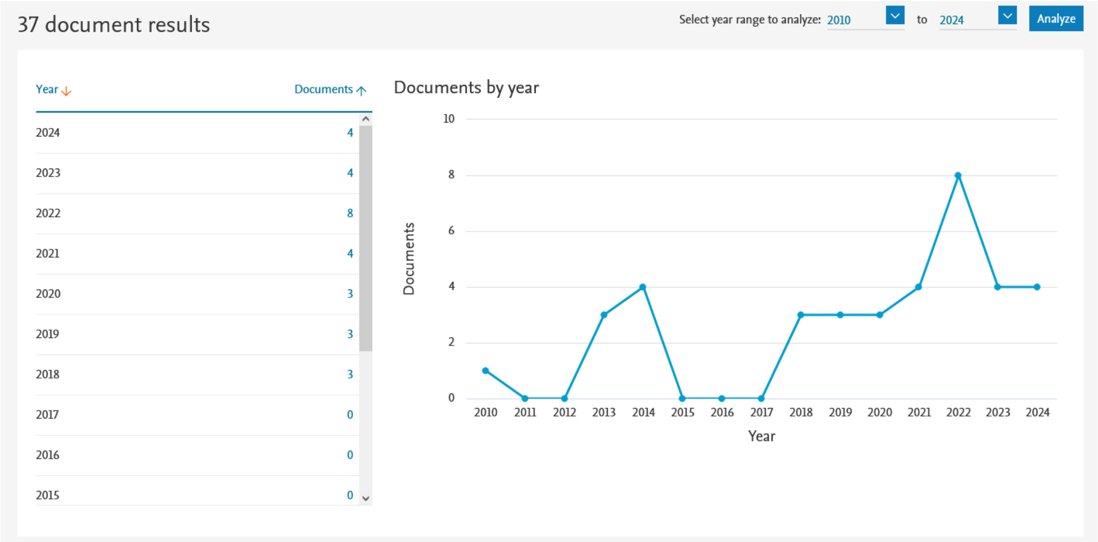
Table 1.
Country Scientific Production

Region	Frequency
INDIA	42
ITALY	16
CHINA	8
MALAYSIA	7
AUSTRALIA	6
GREECE	4
POLAND	4
THAILAND	4
CZECH REPUBLIC	3
FRANCE	3
SWEDEN	3
JAPAN	2
MOROCCO	2
UK	2
GERMANY	1
IRAQ	1

highlighted the important issues and challenges. The prospective and challenges are also discussed.

I. Geopolymer

Geopolymer material is a mixture of alkali activator solution and materials rich in alumina (Al_2O_3) and silica (SiO_2), or simply aluminosilicate. An inorganic polycondensation reaction, also known as "geopolymerization," between solid aluminosilicate precursors and alkaline solutions or highly concentrated aqueous alkali hydroxide, produces a class of aluminosilicate materials known as geopolymers. This process is represented in Fig. **5**. The first inorganic geopolymer material was created by Davidovits by mixing Si and Al rich material such as clay, fly ash, and slag with alkaline activator. The geopolymerization are represented in three main steps: (i) Free silica and alumina tetrahedron units are created when aluminosilicate materials dissolve in the concentrated alkali solution, (ii) An inorganic geopolymer gel phase is produced during the condensation of alumina and silica hydroxyl. Water leaves the structure



37 document results

Year	Documents
2024	4
2023	4
2022	8
2021	4
2020	3
2019	3
2018	3
2017	0
2016	0
2015	0

Fig. 3. The number of research publications with the keywords of geopolymer and medical. Data was collected from Scopus website as per May 2024.

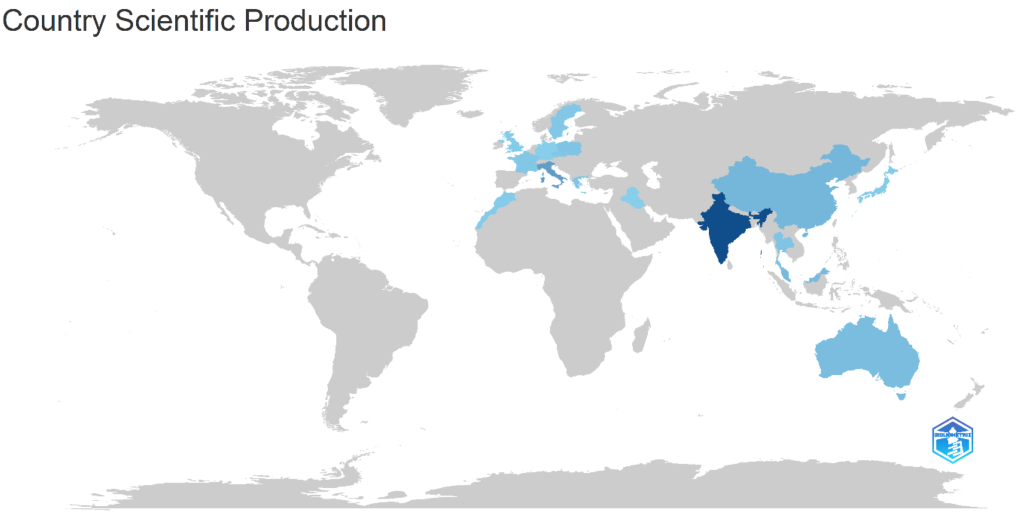


Fig. 4. Country scientific production scholarly paper.

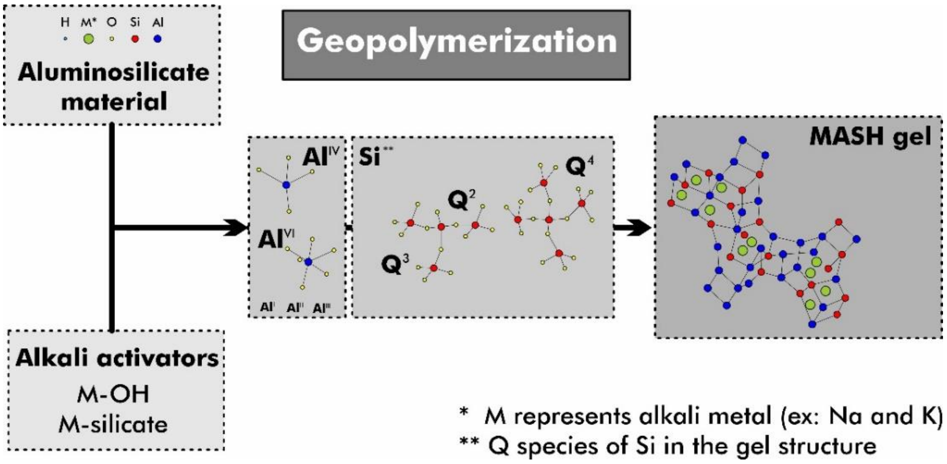


Fig. 5. Geopolymerization process involving aluminosilicate materials and alkali activators resulted in MASH gel.

as a result of this process, (iii) The three-dimensional silicoaluminate network that has been created hardens and condenses.

Geopolymers can also be functionalized, made into organic-inorganic hybrids, or combined with other materials to create composites in order to produce novel materials for cutting-edge technological applications [4-7]. The organic phase may be added to the geopolymer paste in either a liquid or solid form, such as a fibers, whiskers, or particles [8, 9]. The illustration was represented in Fig. **6**.

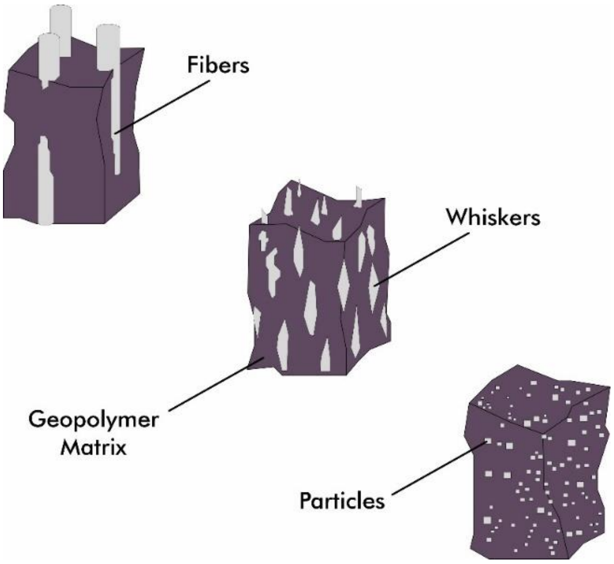


Fig. 6. Schematic illustration of different phase addition to geopolymer.

Geopolymer has been widely used as a coating material since it has good corrosion resistance for metal [10]. The methods for applying geopolymer coating to substrate materials include spray and spin coating [11-13]. To accelerate the curing rate of geopolymer-based coatings, elevated temperatures are often used [14]. Temperatures above room temperature (60–80 °C) are ideal for geopolymerization because they facilitate the dissolution response of raw materials [15]. The ratio of water to solid can affect the workability and adhesion [16]. The fluidity of geopolymers can be maintained in liquid form as long as they are subjected to constant shearing [17-19]. The setting time of the coating depends on its chemical composition, which can be reduced by lowering Si/Al ratios or increasing calcium content. Delayed setting times can be achieved at higher Si/Al ratios.

II. Source of raw materials

The raw materials for geopolymer have to be rich in Al_2O_3 and SiO_2. They typically include metakaolin and/or the waste materials left over from different industrial processes, such as fly ash, bottom ash, red mud, steel slag, waste glass, rice husk ash, tailing, and others. Metakaolin, the calcined form of Kaolin, is the most commonly used aluminosilicate source that has been studied for bone substitute application because of its white color and high amount of silica and alumina [20].

However, even high purity kaolin usually contained trace elements and oxides, such as ferrous oxide (Fe_2O_3), which explained the translucent yellow appearance. Metakaolin also has a low amount of potassium dioxide (K_2O) and titanium dioxide (TiO_2). These oxides can be harmful when applied to the human body since Fe_2O_3 has been reported to have toxic effects on the liver and lung tissue, K_2O can be harmful to the upper respiratory tract, and while TiO_2 has been widely used as a pigment in sunscreen, it has been reported that it can induce inflammation due to oxidative stress and also have a genotoxic effect leading to apoptosis or chromosomal instability [21, 22]. To tackle this impurities problem, synthetic aluminosilicate can be used to ensure the oxides only consist of alumina and silica. Sol-gel method can be used for synthesizing alumina and silica from aluminum nitrate nanohydrate ($Al(NO_3)_3.9H_2O$) and tetraethyl orthosilicate ($Si(OC_2H_5)_4$), respectively [23].

III. Alkali activators

The alkali activator solution consisted of a highly basic hydroxide solution such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na_2SiO_3). Si^{4+} and Al^{3+} ions dissolve rapidly in aluminosilicate materials with a high degree of geopolymerization when the pH is high, which can be achieved by using NaOH concentration above 10 M [24, 25]. Normally, to obtain different molarities of NaOH solution, it must be created by reacting NaOH flakes with aqua DM. The NaOH solution mixing process generates elevated temperatures up to 180 °C, which can be harmful if not done correctly. To make an alkali activator, the sodium hydroxide solution must be mixed with Na_2SiO_3 solution, which requires a waiting time of 4-6 hours. The waiting time was necessary since mixing both solutions generates heat, although the temperature is not as high as NaOH solution. If freshly mixed alkali activator is directly added to the geopolymer precursor, the heat will release CO_2, which can react with Na_2O from the alkali activator components. This will make the hardened geopolymer generate sodium bicarbonate ($NaHCO_3$), called the efflorescence phenomenon. Study reported that geopolymer covered in that compound will have its compressive strength decreased with increasing $NaHCO_3$ [26]. The temperature problems from the synthesis of NaOH and alkali activator solutions and also the waiting time for alkali activator to be readily available are the problems for commercialization and mass production of geopolymers. To address this issue, a new method called a one-part geopolymer was introduced [27]. This mechanism utilized dry activator(s) that underwent geopolymerization by just adding water [28]. The solid alkali materials that have been reported for one-part geopolymer are sodium metasilicate pentahydrate, sodium hydroxide, oxide and silicate, sodium aluminate, calcium hydroxide, potassium carbonate, and sodium metasilicate anhydrous [29-31].

IV. Additives and fillers

Chemical additives such as selenates, sulfates, sucrose, and hydrocarboxylic acids can improve the rheological properties of geopolymers [32]. Fillers of materials can range from ceramic powder or even polymer as reinforcing materials. A volcanic material called trass has been used for geopolymer filler [33]. To increase the mechanical properties of geopolymer, fillers such as quartz sand, chamotte, and cordierite have been used to increase the compressive strength by reducing shrinkage [34]. Polymer-based filler material such as natural rubber and glass-reinforced epoxy has been reported to increase the compressive modulus and compressive strength of geopolymers [35-37].

V. Fabrication of geopolymer

The most convenient technique to synthesize geopolymer is by mixing dry aluminosilicate powder with an alkali activator solution. Manual mixing can produce an unhomogenous slurry. Therefore, mixing techniques using a mixer are preferred. Moreover, since some filler materials can absorb alkali, it is recommended to mix the aluminosilicate with the alkali solution into a homogenous paste before adding the fillers. The slurry was then cast into the mold that was customized for the test purpose. For example, cube specimen molds were widely used to measure the compressive strength of geopolymer conforming to ASTM C109, since geopolymer itself has no specific standard up to date and normally refers to cement-based material standards. The material for the mold needs to not absorb water because hydrophilic mold (ex., from wood or cardboard) can absorb the water from an alkali solution and disrupt the geopolymerization. Normally, molds made of stainless steel and silicon can be used for casting purposes. Aluminum-based mold cannot be used since it can react with NaOH from the alkali activator, Once the reaction is established, hydrogen gas rapidly evolves and the reaction becomes highly exothermic. The reaction is described below:

$$2Al + 2NaOH + 2H_2O \rightarrow 2NaAlO_2 + 3H$$

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VI. Application of geopolymer for medical field

Geopolymers have a wide range of uses like building materials, thermal applications, aerospace applications among others. Recently, the applications of these materials for biomedical applications, has gained interest worldwide as mentioned in Fig.1. The following subsections elucidated some application of geopolymer as antibacterial, drug delivery, implant, and dental material.

VII. Antibacterial

Antibacterial systems are critical not only in hospitals and sanitary settings, but also in domestic, industrial, textile, and marine applications [38]. Several studies were conducted in order to improve the antibacterial capacity of construction materials such as glazes on ceramic tiles and alkali-activated slag pastes [39]. Geopolymer has high alkalinity and ease of functionalization by incorporating semiconductor materials such as ZnO, TiO_2, and CuO. These oxides can cause bacterial inactivation and virus elimination in various environments [40, 41]. When geopolymer mixed with semiconductor materials exposed to UV and UV-Vis radiation, it exhibited functional activity such as photocatalytic properties [42]. Gutiérrez et al. studied the effect of TiO_2 and CuO nanoparticles

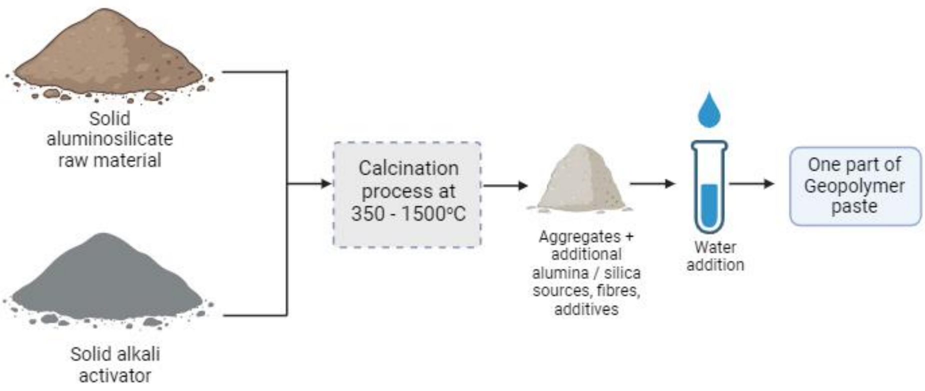

Fig. 7. The general procedure of one-part geopolymer preparation.

with the addition of waste glass on the antibacterial activities of metakaolin-based geopolymer [43]. The bacteria study revealed that after 24 hours in culture media, the GP-G mortars had a high inhibition capacity for the growth of P. aeruginosa from solutions of 104 mL and E. coli and S. aureus from solutions of 106 mL. The schematic illustration of geopolymer bacterial inhibition performance compared to non-bacterial resistant material (NBRM) are shown in Fig. **8**.

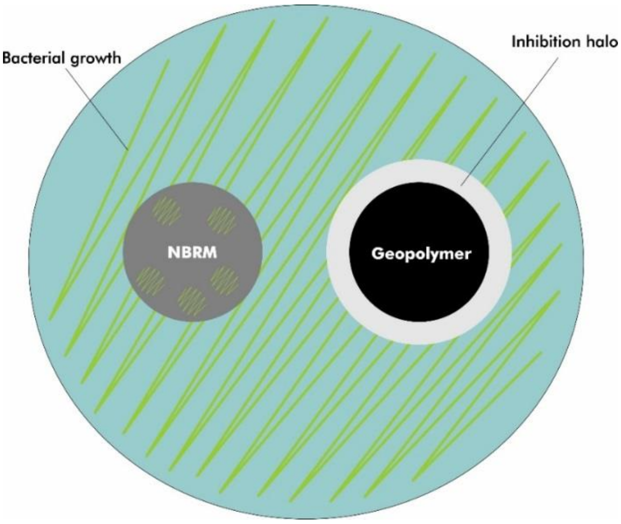

Fig. 8. Schematic illustration of bacterial inhibition performance of geopolymer.

The incorporation of geopolymer other substrates to create antibacterial properties surface can be applied using advanced deposition techniques such as chemical vapor deposition, ion implantation, sputtering, and electrochemical solution deposition. These methods, however, are costly and difficult to apply for large-volume particles or complex shapes. Dip coating is one of the less-cost methods compared to others. In fact, Rondinella et al. utilized this method for the coating of Ti6Al4V alloys for futuristic prosthetic devices [44]. Their findings showed that the geopolymer-based coatings slowed bacterial growth, while highlighting that alkaline-based coating is found to adhere well to the substrate, in contrast to the acid-based coating, which is removed during the scratch test even for low loads, most likely due to unreacted material. The schematic of multilayered coating structure was presented in Fig. **9**.

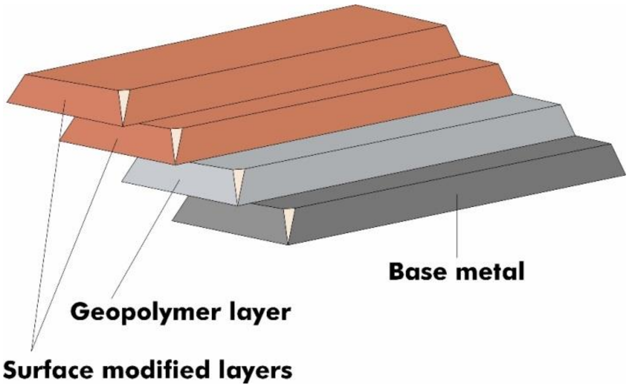

Fig. 9. Brief schematic of the multilayered coating structure.

Silver (Ag) has been widely known for its antibacterial properties [45, 46]. Nanoparticle silver can be integrated to geopolymer to enhance its antibacterial properties as shown in. Adak et al. studied the efficiency of nano silver-silica modified geopolymer mortar for eco-friendly green construction [47]. The mechanical strength, durability, and anti-bacterial property of the geopolymer mortar significantly improve with the addition of 6% (w/w) of the silver-silica nanocomposite. Aside from oxide semiconductors and antibacterial elements, antibacterial organic compounds also can be introduced to geopolymer for carrier material. Rubio-Avalos loaded 5-chloro-2-(2, 4-Dichlorophenoxy) phenol also known as “Triclosan” into geopolymer [48]. Their findings showed that Geopolymer cements with triclosan as a base are effective at stopping the growth of S. aureus and E. coli bacteria. The outcomes allow for the creation of a "room-temperature" antibacterial metakaolin-based geopolymer cement for use in construction projects that protect human health and the environment.

VIII. Drug delivery

Forsgren et al. studied synthetic aluminosilicate-based geopolymer from sol-gel technique for controlled delivery of oxycodone [49]. It was demonstrated that as the Al/Si ratio increased, the pore sizes of the geopolymers shrank, and that completely mesoporous geopolymers

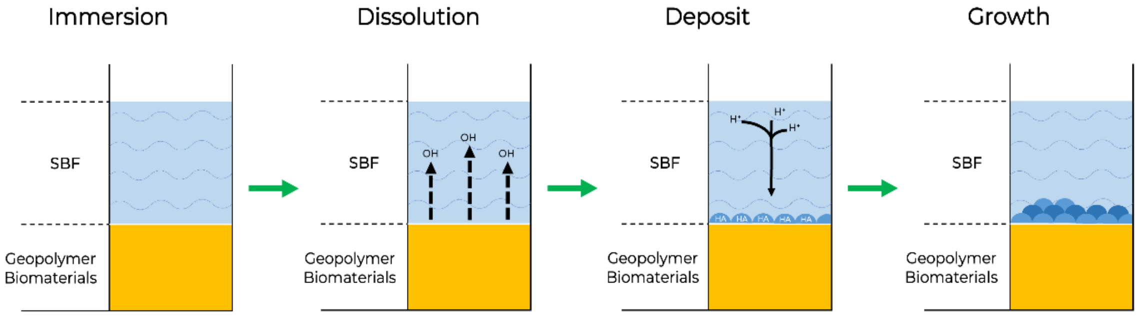

Fig. 10. Mechanism of HAp formation from geopolymer biomaterials immersed in SBF.

could be created from precursor particles with an Al/Si ratio of 2:1. The opioid oxycodone sustained and linear in vitro release profile was shown to be correlated with mesoporosity. By changing the size of the pellets, an approximately 12-hour clinically relevant release period was attained. Controlled-release formulations of opioid drugs have an important feature known as tamper resistance. Cai et al. evaluated the resistance of geopolymer-based drug delivery systems to tampering [50]. The drug-release test showed that the milled commercial tablets released the drug immediately, which could lead to dose dumping, whereas the geopolymer-based formulation maintained its controlled-release characteristics after milling. Jämstorp et al. used metakaolin-based geopolymer for drug release of fentanyl, sumatriptan, theophylline, and saccharin [51]. This material provides the opportunity to create a solid matrix that won't dissolve during transit through the digestive system after being formed into pellets. Their findings show that theophylline is discovered to have release times between saccharin and fentanyl, with a slight restriction in the relative solubility, offering only a minor change in the release profile in comparison to that of saccharin.

IX. Bioceramics

The most important prerequisite for a biomaterial to be taken into consideration for use as a potential tissue replacement is biocompatibility. Designing and using materials in a way that respects the balance between their strength and integrity with the necessary bone tissue ingrowth over time is another aspect of biocompatibility. Materials used as bone scaffolds should encourage osteogenesis and reduce or eliminate negative effects, such as the deterioration of native and healthy tissues and the body's inflammatory response, because such materials can be perceived as foreign and be a threat [52, 53]. In order for the body to naturally digest and absorb the system without causing pH changes in the cellular environment, it must be biodegradable. The pH levels at or near the implant site may change as a result of the leaching of dangerous byproducts biodegradation processes. The changes in pH may cause cells to divide more slowly, reproduce less frequently, and ultimately prevent growth. [54-56]. Human function must be supported by an implanted biomaterial under normal compressive pressure. It becomes crucial to have biomaterials with mechanical characteristics that enable them to serve structural purposes while remaining adaptable enough to prevent shear fracture under continuous compressive stresses [57, 58]. Catauro et al. studied the assessment of bioactivities of geopolymer [59]. The immersion of geopolymer in simulated body fluid (SBF) generated the formation of hydroxyapatite (HAp), a compound that is used for scaffold biocompatibility index and reported a modest bioactivity of resulting materials. This is illustrated in Fig. **10**.

The study of geopolymers for dental material has been extensively studied, particularly in Indonesia [60]. This is due to the high amount of natural resources such as kaolin and silica. Taking advantage of its local wisdom can reduce the cost of a dental-based product compared to importing the raw material from overseas. Sutanto et al. studied the application of geopolymer as an indirect dental restoration [61]. Their metakaolin-based geopolymer was synthesized with strontium (Sr) and carbonated apatite (CHA). The latter element has been reported to increase the biocompatibility, bio integrity, and mechanical properties of metakaolin-based geopolymers, as studied by Sunendar et al. [62]. Their findings stated that geopolymer samples had high cell viability readings and

Table 2.

Cell viabilities of geopolymer-based material from various researchers

Study	Year	Aluminosilicate sources	Doping material	Cell viabilities (%)	Ref.
Refaat et al.	2023	GGBFS	NaOH	± 50	[63]
Sutanto et al.	2021	Metakaolin	Carbonated apatite	± 90	[64]
Poggetto et al.	2021	Metakaolin	Waste glass	70 – 100	[65]
Sutanto et al.	2020	Metakaolin	Carbonated HAp and Strontium	± 80	[61]
Catauro et al.	2017	Metakaolin	Waste Electrical and Electronic Equipment (WEEE) glass	20 - 75	[66]

Table 3.

Chemical composition of biomedical waste ash by various researchers.

Study	Al_2O_3 (%)	SiO_2 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO	Ref.
Anastiadou et al. (2012)	5.16	39.74	27.77	4.53	-	-	[69]
Jaber et al. – ASCH (2021)	0.1267	1.716	14.87	1.180	1.703	< 0.10	[70]
Kumar et al. (2022)	21.8	36.23	19.54	1.2	0.36	7.9	[71]
Kumar et al. (2023)	23.26	38.52	23.2	1.85	5.08	3.21	[72]
Rishi and Aggarwal (2023)	10	20	35	6.4	0.6	2.2	[73]
Debrah and Dinis - TGH (2023)	2.04	2.54	27.96	0.42	1.01	2.87	[74]
Debrah and Dinis - VRAH (2023)	3.74	6.10	27.07	0.83	0.74	2.93	[74]
Nataraja et al. (2023)	7.82	12.11	47.8	1.94	0.25	0.18	[75]

appeared to be biocompatible. Table 2 shown the cell viabilities of geopolymer material from various sources.

The study of geopolymer-based composite's biocompatibility was also studied by Pangdaeng et al. using the calcined kaolin-white Portland cement geopolymer. The results showed that the hydroxyapatite layer was formed on the 28-days immersed geopolymer's surface when in vitro test occurred. In vitro test was done using the simulated body fluid to comprehend the biocompatibility in human's body. Furthermore, the strength of the calcined-kaolin geopolymer cured at 23°C was also observed at 45.5 MPa and increased to 63.8 MPa as the addition of 50% WPC [65]. The utilization of porous bioceramics using the geopolymer hydroxyapatite composite has been reported by Andrade et al for application in bone tissue engineering. Their mixture consisted of metakaolin, hydroxyapatite, and geopolymer filler with the variation of metakaolin types (MK1, MK2, and MK3) followed by heat treatment. The resulted geopolymers has been proven to own the compressive strength values between 1.18 and 2.89 MPa, indicating the suitable balance between mechanical strength and porosity. Furthermore, the results of in-vitro test using human adipose-derived mesenchymal stem cells (ADSCs) also showed the non-toxicity and no morphological changes when the composite contacted with the human cells. The reports also said that the geopolymer hydroxyapatite composite will form a monolayer in the surface of the scaffolds. The mechanism of bone cells and geopolymer scaffold resulted in cell proliferation are illustrated in Fig. **11**. Therefore, it can be concluded that the geopolymer hydroxyapatite composite is effective to be used for bone tissue application due to its good compressive strength and biocompatibility [66].

X. Biomedical waste ash utilization

The emergence of the COVID-19 pandemic in 2020 resulted in a high amount of biomedical waste from hospitals, medical institutes, and research centers. The waste might comes from anatomical waste, animal wastes generated during research from veterinary clinics, microbiology and biotechnology wastes, and waste sharps [67]. Since it contains harmful and dangerous substances, incineration has been used for the disposal of waste [68].

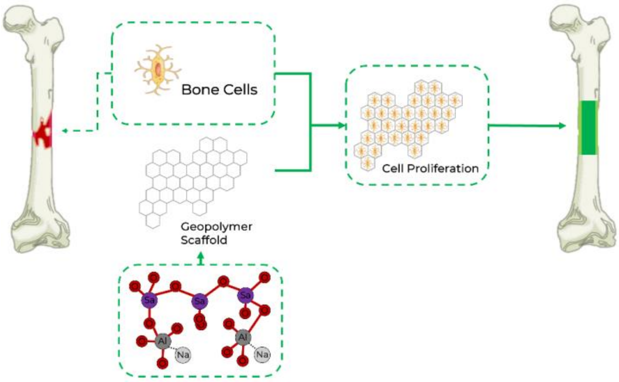

Fig. 11. Illustration of bone cells and geopolymer scaffold interaction.

The resulting product generates ash, which interestingly contains Al_2O_3 and SiO_2, which are beneficial to the formation of geopolymers. Some chemical compostion data of biomedical waste ash were presented in Table 3. Knowing this, some researchers have utilized the aforementioned ash for geopolymer applications, either as replacement for aluminosilicate or fine aggregate substitutor.

Kumar et al. studied the effect of incinerated biomedical waste ash (IBWA) in reinforced geopolymer concrete [76]. The ash was used to partially replace ground granulated blast furnace slag (GGBS). Their experimental results showed that reinforced geopolymer beams and columns with a composition of 30% IBWA and 70% GGBS performed better than reinforced cement concrete beams and columns. Kumar et al. compared the mechanical properties of IBWA and ground granulated blast furnace (GGBFS)-based geopolymer to reinforced cement concrete (RCC) [71]. The geopolymer concrete maximum compressive strength at 28 days was 48.6 MPa, which is 45.07% higher than RCC. Rishi and Aggarwal investigated the properties of geopolymer consisting of fly ash, bone china waste (BCW), and biomedical waste (BMW) ash with different alkali activator molarity [73]. The addition of BMW and BCW up to 30% each (total of 60%) in the geopolymer mixes resulted in a significant improvement in workability when compared to the control mix. In the cases of workability, density, air content, and strength, the molarity of sodium hydroxide was crucial. All parameters except air content showed a significant increase as sodium hydroxide's molarity was raised from

8 to 16 M. Table 3 shows various oxide compositions, but mainly consists of Al_2O_3, SiO_2, CaO, Fe_2O_3, K_2O, and MgO. Although the Al_2O_3 and SiO_2 has fluctuated, the amount of CaO in all BMW ash has ranged from 10–20%. This means that it can be used as a partial replacement of the geopolymer precursor, which will generate not only N-A-S-H gel but also C-A-S-H gel. These two geopolymerization products will complement each other and result in changes to the mechanical properties of geopolymers.

XI. Prospective and challenges

The prospect of geopolymer for medical applications looks promising due to its simple fabrication method, which requires only mixing solid powder with an alkali activator. Most of the geopolymer research for medical applications used metakaolin as the precursor. The challenges, however, remain the high temperature requirement of kaolin calcination, which increases the cost of manufacture. The trace element in kaolin also has to be studied extensively to observe the leachate element after contact with the environment. The setting time of geopolymer paste has to be controlled since different material sources translate to different Al_2O_3 and SiO_2 percentages, which means it will affect the setting time. The addition of an accelerating or retarding agent might help to address this issue, provided that the admixture will not cause a new problem for the environment. For example, calcium sulfate ($CaSO_4$) may provide a retarding effect to the geopolymer paste, but the SO_4^{2-} ion can induce corrosion in low-carbon steel-based medical devices as elucidated in Fig. **12**.

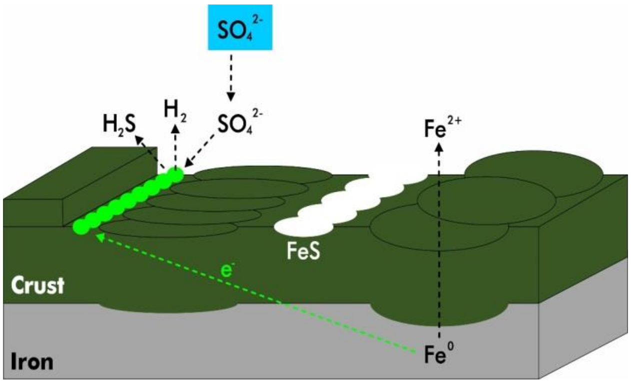

Fig. 12. Schematic illustration of sulfate ion attack on iron.

Synthetic aluminosilicate using the sol-gel method is an advanced route to produce high purity Al_2O_3 and SiO_2. This route can produce micro- or nanoparticle-sized precursors, which need to be controlled since the fineness of the powder may generate shrinkage of the resulting material. The starting material, sol-gel such as TEOS, is also expensive, and the small number of resulting products can hinder the mass production of this technique. The application of geopolymer coating to the metal-based devices has to be done using the proper technique, since direct coating can result in spalling of the hardened geopolymer layer. Heat treatment of metal before applying geopolymer paste to the substrate or a more advanced technique such as thermal barrier coating is proposed to improve the bond between geopolymer and metal. Although it contains an abundant and considerable amount of Al_2O_3 and SiO_2, the utilization of fly ash-based geopolymers for medical applications remains debatable, not only because they may contain harmful trace elements but also because their source is industrial waste that might be inappropriately used in the human body.

Conclusions

In this review paper, the authors summarized that geopolymer has the potential for various medical application techniques. The adjustable strength and porosity make this material versatile for coating substrates to become bone scaffold material. However, the concern remains about the leaching and high alkalinity of geopolymers. This could be improved by mixing geopolymer with compounds to trap the harmful leachate agent inside and studying different solutions for the activation of geopolymer. Future prospects, however, remains about in-vivo and in-vitro characteristics of geopolymer before readily applied for human body application. Hopefully, this review paper encourages more researchers to study geopolymer and its application in medical fields.

Acknowledgments

This work is supported by the National Research and Innovation Agency Indonesia under the "Rumah Program Pengembangan Alat dan Deteksi Kesehatan Batch 2" program.

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[1] J. Zhao, et al., *Eco-friendly geopolymer materials: A review of performance improvement, potential application and sustainability assessment.* Journal of Cleaner Production, 307, 127085 (2021); https://doi.org/10.1016/j.jclepro.2021.127085.

[2] B. Bakhtyar, T. Kacemi, and M.A. Nawaz, *A review on carbon emissions in Malaysian cement industry.* International Journal of Energy Economics and Policy, 7(3), 282 (2017).

[3] M. Grant Norton, and J.L. Provis, *1000 at 1000: Geopolymer technology—the current state of the art.* Journal of Materials Science, 55(28), 13487 (2020); https://doi.org/10.1007/s10853-020-04990-z.

[4] G. Roviello, et al., *Hybrid geopolymers from fly ash and polysiloxanes*. Molecules, 24(19), 3510 (2019); https://doi.org/10.3390/molecules24193510.

[5] L. Ricciotti, et al., *Geopolymer-based hybrid foams: Lightweight materials from a sustainable production process.* Journal of cleaner production, 250, 119588 (2020); https://doi.org/10.1016/j.jclepro.2019.119588.

[6] G. Roviello, et al., *Hybrid geopolymeric foams for the removal of metallic ions from aqueous waste solutions*. Materials, 12(24), 4091 (2019); https://doi.org/10.3390/ma12244091.

[7] L. Ricciotti, et al., *Development of Geopolymer-Based Materials with Ceramic Waste for Artistic and Restoration Applications*. Materials, 15(23); 8600 (2022); https://doi.org/10.3390/ma15238600.

[8] D.-W. Zhang, D.-M. Wang, and F.-Z. Xie, *Microrheology of fresh geopolymer pastes with different NaOH amounts at room temperature.* Construction and Building Materials, 207, 284 (2019); https://doi.org/10.1016/j.conbuildmat.2019.02.149.

[9] D.-W. Zhang, et al., *Rheology, agglomerate structure, and particle shape of fresh geopolymer pastes with different NaOH activators content*. Construction and Building Materials, 187, 674 (2018); https://doi.org/10.1016/j.conbuildmat.2018.07.205.

[10] M.S. Siti Salwa, et al., *Review on Current Geopolymer as a Coating Material.* Australian Journal of Basic and Applied Sciences, 7(5), 246 (2013).

[11] A. El Khomsi, et al., *Geopolymer Composite Coatings Based on Moroccan Clay and Sands for Restoration Application*. Frontiers in Chemical Engineering, 3, (2021); https://doi.org/10.3389/fceng.2021.667982.

[12] P. Bhardwaj, *Optimization studies and characterization of advanced geopolymer coatings for the fabrication of mild steel substrate by spin coating technique*. Indian Journal of Chemical Technology (IJCT), 28(1), (2021); https://doi.org/10.56042/ijct.v28i1.31721.

[13] J. Novotný, et al., *Manufacture and Characterization of Geopolymer Coatings Deposited from Suspensions on Aluminium Substrates*. Coatings, 12(11), 1695 (2022); https://doi.org/10.3390/coatings12111695.

[14] L. Biondi, et al., *Ambient Cured Fly Ash Geopolymer Coatings for Concrete*. Materials, 12(6), 923 (2019); https://doi.org/10.3390/ma12060923.

[15] R. Petrescu, et al., *News in bone modeling for customized hybrid biological prostheses development*. OnLine J. Biol. Sci, 21, 285 (2021); https://doi.org/10.3844/ojbsci.2021.285.316.

[16] S. Mu, et al., *Property and microstructure of aluminosilicate inorganic coating for concrete: Role of water to solid ratio.* Construction and Building Materials, 148, 846 (2017); https://doi.org/10.1016/j.conbuildmat.2017.05.070.

[17] M. Criado, et al., *Alkali activated fly ash: effect of admixtures on paste rheology.* Rheologica Acta, 48(4), 447 (2009); https://doi.org/10.1007/s00397-008-0345-5.

[18] H. Mundra, et al., *Rheological properties of Class F fly-ash based alkali-activated materials (AAMs) for oil and gas well cementing applications*. CEMENT, 12, 100068 (2023); https://doi.org/10.1016/j.cement.2023.100068.

[19] X. Dai, et al., *Rheology and microstructure of alkali-activated slag cements produced with silica fume activator.* Cement and Concrete Composites, 125, 104303 (2009); https://doi.org/10.1016/j.cemconcomp.2021.104303.

[20] Y. Faza, et al., *Synthesis of Porous Metakaolin Geopolymer as Bone Substitute Materials.* Key Engineering Materials, 829, 182 (2020); https://doi.org/10.4028/www.scientific.net/KEM.829.182.

[21] E. Baranowska-Wójcik, et al., *Effects of Titanium Dioxide Nanoparticles Exposure on Human Health—a Review.* Biological Trace Element Research, 193(1), 118 (2020); https://doi.org/10.1007/s12011-019-01706-6.

[22] D. Askri, et al., *Effects of Iron Oxide Nanoparticles (γ-Fe2O3) on Liver, Lung and Brain Proteomes following Sub-Acute Intranasal Exposure: A New Toxicological Assessment in Rat Model Using iTRAQ-Based Quantitative Proteomics.* International Journal of Molecular Sciences, 20(20), 5186 (2019); https://doi.org/10.3390%2Fijms20205186.

[23] A. Harmaji, O.D. Putri, and B. Sunendar, *Mechanical And Microstructural Assessment Of Synthetic Aluminosilicate Based Geopolymer Dental Material*. Fullerene Journal of Chemistry, 7(2), 52 (2023); https://doi.org/10.37033/fjc.v7i2.425.

[24] Y.-S. Wang, J.L. Provis, and J.-G. Dai, *Role of soluble aluminum species in the activating solution for synthesis of silico-aluminophosphate geopolymers.* Cement and Concrete Composites, 93, 186 (2018); https://doi.org/10.1016/j.cemconcomp.2018.07.011.

[25] F.A. Shilar, S.V. Ganachari, and V.B. Patil, *Advancement of nano-based construction materials-A review.* Construction and Building Materials, 359, 129535 (2022); https://doi.org/10.1016/j.conbuildmat.2022.129535.

[26] Y. Wang, et al., *Comparison of Effects of Sodium Bicarbonate and Sodium Carbonate on the Hydration and Properties of Portland Cement Paste.* Materials, 12(7); 1033 (2019); https://doi.org/10.3390/ma12071033.

[27] E. Adesanya, et al., *One-part geopolymer cement from slag and pretreated paper sludge*. Journal of Cleaner Production, 185, 168 (2018); https://doi.org/10.1016/j.jclepro.2018.03.007.

[28] O. Wan-En, et al., *The Effect of Sodium Carbonate on the Fresh and Hardened Properties of Fly Ash-Based One-Part Geopolymer*. IOP Conference Series: Materials Science and Engineering, 864 (1), 012197 (2020); https://doi.org/10.1088/1757-899X/864/1/012197.

[29] S. Ouyang, et al., *Experimental study of one-part geopolymer using different alkali sources.* Journal of Physics: Conference Series, 1605(1), 012155 (2020); https://doi.org/10.1088/1742-6596/1605/1/012155.

[30] L.Y. Ming, et al., *Characteristic of One-Part Geopolymer as Building Materials, in Sustainable Waste Utilization in Bricks, Concrete, and Cementitious Materials: Characteristics, Properties, Performance, and Applications*, A. Abdul Kadir, N. Amira Sarani, and S. Shahidan, Editors. 2021, Springer Singapore: Singapore. 97 (2021); https://doi.org/10.1007/978-981-33-4918-6_6.

[31] W. Teo, et al., *Experimental Investigation on Ambient-Cured One-Part Alkali-Activated Binders Using Combined High-Calcium Fly Ash (HCFA) and Ground Granulated Blast Furnace Slag (GGBS)*. Materials, 15(4), 1612 (2022); https://doi.org/10.3390/ma15041612.

[32] L.N. Assi, E. Deaver, and P. Ziehl, *Using sucrose for improvement of initial and final setting times of silica fume-based activating solution of fly ash geopolymer concrete*. Construction and Building Materials, 191, 47 (2018); https://doi.org/10.1016/j.conbuildmat.2018.09.199.

[33] P. Risdanareni, J.J. Ekaputri, and Triwulan, *The Influence of Alkali Activator Concentration to Mechanical Properties of Geopolymer Concrete with Trass as a Filler*. Materials Science Forum, 803, 125 (2015); http://dx.doi.org/10.4028/www.scientific.net/MSF.803.125.

[34] J. Kohout, and P. Koutník, *Effect of Filler Type on the Thermo-Mechanical Properties of Metakaolinite-Based Geopolymer Composites*. Materials, 13(10), 2395 (2020); https://doi.org/10.3390/ma13102395.

[35] H. Yangthong, et al., *Novel natural rubber composites with geopolymer filler.* Advances in Polymer Technology, 37(7), 2651 (2018); https://doi.org/10.1002/adv.21940.

[36] M.F.A. Hashim, et al., *Effect of Geopolymer filler in Glass Reinforced Epoxy (GRE) Pipe for Piping Application: Mechanical Properties.* IOP Conference Series: Materials Science and Engineering, 133(1); 012044 (2016); http://dx.doi.org/10.1088/1757-899X/133/1/012044.

[37] M.F.A. Hashim, et al., *Interaction of Geopolymer Filler and Alkali Molarity Concentration towards the Fire Properties of Glass-Reinforced Epoxy Composites Fabricated Using Filament Winding Technique*. Materials, 15(18); 6495 (2022) https://doi.org/10.3390/ma15186495.

[38] R. Gulati, S. Sharma, and R.K. Sharma, *Antimicrobial textile: recent developments and functional perspective*. Polym Bull (Berl), 79(8), 5747 (2022); https://doi.org/10.1007/s00289-021-03826-3.

[39] H.A. Abdel-Gawwad, S.A. Mohamed, and M.S. Mohammed, *Recycling of slag and lead-bearing sludge in the cleaner production of alkali activated cement with high performance and microbial resistivity.* Journal of Cleaner Production, 220, 568 (2019); https://doi.org/10.1016/j.jclepro.2019.02.144.

[40] P. Sikora, et al., *Antimicrobial activity of Al2O3, CuO, Fe3O4, and ZnO nanoparticles in scope of their further application in cement-based building materials.* Nanomaterials, 8(4), 212 (2018); https://doi.org/10.3390%2Fnano8040212.

[41] M.H. Toodehzaeim, et al., *The effect of CuO nanoparticles on antimicrobial effects and shear bond strength of orthodontic adhesives*. Journal of Dentistry, 19(1), 1 (2018).

[42] M.S. Dahiya, V.K. Tomer, and S. Duhan, *Bioactive glass/glass ceramics for dental applications, in Applications of nanocomposite materials in dentistry*. Elsevier. 1 (2019); https://doi.org/10.3390/ijms20235960.

[43] R.M.-d .Gutiérrez, et al., *Evaluation of the Antibacterial Activity of a Geopolymer Mortar Based on Metakaolin Supplemented with TiO2 and CuO Particles Using Glass Waste as Fine Aggregate*. Coatings, 10(2) 157 (2020); https://doi.org/10.3390/coatings10020157.

[44] A. Rondinella, et al., *Mechanical and antibacterial behavior of multilayered geopolymer coatings on Ti6Al4V alloys.* Journal of Materials Science, 57(39), 18578(2022); https://doi.org/10.1007/s10853-022-07767-8.

[45] A. Kędziora, et al., *Comparison of Antibacterial Mode of Action of Silver Ions and Silver Nanoformulations With Different Physico-Chemical Properties: Experimental and Computational Studies*. Frontiers in Microbiology, 12, (2021); https://doi.org/10.3389/fmicb.2021.659614.

[46] J.C. Mather, et al., *Antibacterial silver and gold complexes of imidazole and 1,2,4-triazole derived N-heterocyclic carbenes*. Dalton Transactions, 51(32), 12056 (2022); https://doi.org/10.1039/D2DT01657E.

[47] D. Adak, et al., *Anti-microbial efficiency of nano silver–silica modified geopolymer mortar for eco-friendly green construction technology*. RSC Advances, 5(79), 64037(2015); https://doi.org/10.1039/C5RA12776A.

[48] J.-C. Rubio-Avalos, *Antibacterial Metakaolin-Based Geopolymer Cement. in Calcined Clays for Sustainable Concrete.* Dordrecht: Springer Netherlands. (2018); http://dx.doi.org/10.1007/978-94-024-1207-9_64.

[49] J. Forsgren, et al., *Synthetic geopolymers for controlled delivery of oxycodone: adjustable and nanostructured porosity enables tunable and sustained drug release*. PLoS One, 6(3), e17759 (2011); https://doi.org/10.1371/journal.pone.0017759.

[50] B. Cai, H. Engqvist, and S. Bredenberg, *Evaluation of the resistance of a geopolymer-based drug delivery system to tampering*. International Journal of Pharmaceutics, 465(1), 169(2014); https://doi.org/10.1016/j.ijpharm.2014.02.029.

[51] E. Jämstorp, M. Strømme, and S. Bredenberg, *Influence of drug distribution and solubility on release from geopolymer pellets—A finite element method study*. Journal of Pharmaceutical Sciences, 101(5), 1803 (2012); https://doi.org/10.1002/jps.23071.

[52] C. Gao, et al., *Bone biomaterials. and interactions with stem cells*. Bone research, 5(1), 1 (2017); https://doi.org/10.1038/boneres.2017.59.

[53] H. Qu, et al., *Biomaterials for bone tissue engineering scaffolds: A review*. RSC advances, 9(45), 26252 (2019); https://doi.org/10.1039%2Fc9ra05214c.

[54] J. Hum, and A.R. Boccaccini, *Collagen as coating material for 45S5 bioactive glass-based scaffolds for bone tissue engineering.* International journal of molecular sciences, 19(6), 1807 (2018); https://doi.org/10.3390%2Fijms19061807.

[55] R. Aversa, et al., *Biomechanically Tunable Nano-Silica/P-HEMA Structural Hydrogels for Bone Scaffolding*. Bioengineering, 8(4), 45 (2021); https://doi.org/10.3390/bioengineering8040045.

[56] L. Wang, et al., *Bioresorption Control and Biological Response of Magnesium Alloy AZ31 Coated with Poly-β-Hydroxybutyrate*. Applied Sciences, 11(12), 5627 (2021); https://doi.org/10.3390/app11125627.

[57] R. Aversa, et al., *Biomimetic and evolutionary design driven innovation in sustainable products development.* American Journal of Engineering and Applied Sciences, **9**(4), 1027 (2016); https://doi.org/10.3844/ajeassp.2016.1027.1036.

[58] A. Haider, et al., *Advances in the scaffolds fabrication techniques using biocompatible polymers and their biomedical application: A technical and statistical review.* Journal of saudi chemical society, 24(2), 186 (2020); http://dx.doi.org/10.1016/j.jscs.2020.01.002.

[59] M. Catauro, et al., *Chemical and biological characterization of geopolymers for potential application as hard tissue prostheses*. Advances in science and technology, 69, 192 (2011); https://doi.org/10.4028/www.scientific.net/AST.69.192.

[60] E. Febrina, et al., *Properties of nanocellulose and zirconia alumina on polymethylmethacrylate dental composite*. Dental Journal, 56(1), 30 (2023); http://dx.doi.org/10.20473/j.djmkg.v56.i1.p30-35.

[61] D. Sutanto, et al., *Geopolymer–carbonated apatite nanocomposites with magnesium and strontium trace elements for dental restorative materials.* Journal of the Korean Ceramic Society, 57(5), 546 (2020); https://doi.org/10.1007/s43207-020-00060-x.

[62] B. Sunendar, et al. *The effect of CHA-doped Sr addition to the mechanical strength of metakaolin dental implant geopolymer composite*. in AIP Conference Proceedings. AIP Publishing LLC. (2017); https://doi.org/10.1063/1.5003503.

[63] M. Refaat, et al., *Utilization of optimized microwave sintering to produce safe and sustainable one-part alkali-activated materials*. Scientific Reports, 13(1), 4611 (2023); https://doi.org/10.1038/s41598-023-31581-0.

[64] D. Sutanto, et al., *In vivo histomorphological evaluation of geopolymer-carbonated apatite nanocomposites implanted on rabbit tibia at early bone healing.* Padjajaran Journal of Dentistry, 33(1), 64 (2021); http://dx.doi.org/10.24198/pjd.vol33no1.28899.

[65] G. Dal Poggetto, et al., *Efficient Addition of Waste Glass in MK-Based Geopolymers: Microstructure, Antibacterial and Cytotoxicity Investigation. Polymers (Basel),* 13(9), 1493 (2021); https://doi.org/10.3390/polym13091493.

[66] M. Catauro, I. Lancellotti, and C. Leonelli, *Addition of WEEE Glass to Metakaolin-Based Geopolymeric Binder: A Cytotoxicity Study*. Environments, 4(4), 89 (2017); https://doi.org/10.3390/environments4040089.

[67] K.N. Katare, N.K. Samaiya, and Y. IyerMurthy, *Strength and durability properties of concrete using incinerated biomedical waste ash*. Environmental Engineering Research, 28(2), 220024-0 (2023); https://doi.org/10.4491/eer.2022.024.

[68] V. Gautam, R. Thapar, and M. Sharma, *Biomedical waste management: Incineration vs. environmental safety.* Indian Journal of Medical Microbiology, 28(3), 191 (2010); https://doi.org/10.4103/0255-0857.66465.

[69] K. Anastasiadou, et al., *Solidification/stabilization of fly and bottom ash from medical waste incineration facility*. Journal of Hazardous Materials, 207-208, 165 (2012); https://doi.org/10.1016/j.jhazmat.2011.05.027.

[70] S. Jaber, et al., *The environmental situation of the ash medical waste in Baghdad city*, Iraq. E3S Web Conf.,. 286, 02017 (2021); https://doi.org/10.1051/e3sconf/202128602017.

[71] S.K. A, et al., *Influence of incinerated biomedical waste ash and waste glass powder on the mechanical and flexural properties of reinforced geopolymer concrete*. Australian Journal of Structural Engineering, 23(3), 254 (2022); https://doi.org/10.1080/13287982.2022.2044613.

[72] A. Suresh Kumar, et al. *Development of Environmental-Friendly Geopolymer Concrete Using Incinerated Biomedical Waste Ash*. Singapore: Springer Nature Singapore. 709 (2023); https://doi.org/10.1007/978-981-19-4040-8_56.

[73] Rishi and V. Aggarwal, *Experimental investigation of geopolymer concrete along with biomedical and bone China waste at different molarities of sodium hydroxide*. Multiscale and Multidisciplinary Modeling, Experiments and Design, 6, 277 (2023); https://doi.org/10.1007/s41939-023-00147-y.

[74] J.K. Debrah, and M.A.P. Dinis, *Chemical characteristics of bottom ash from biomedical waste incinerators in Ghana*. Environmental Monitoring and Assessment, 195(5): p. 568 (2023); https://doi.org/10.1007/s10661-023-11132-w.

[75] M.C. Nataraja, et al., *Self-compacting concrete incorporating incinerated biomedical waste ash: a performance assessment*. Journal of Engineering and Applied Science, 70(1), 22 (2023); https://doi.org/10.1186/s44147-023-00191-y.

[76] A.S. Kumar, et al., *Improving the Performance of Structural Members by Incorporating Incinerated Bio-Medical Waste Ash in Reinforced Geopolymer Concrete*. Materials Science Forum, 1048, 321 (2022); https://doi.org/10.4028/www.scientific.net/MSF.1048.321.

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Геополімер для медичного застосування: огляд

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Матеріали для медичного застосування зазвичай формують з металу, кераміки та полімеру. Кожен матеріал має свої обмеження, такі як корозія металу, крихкість кераміки та висока температура полімеру. Щоб усунути їхні слабкості, рекомендується комбінувати один або кілька відповідних матеріалів, які називають композитними. Одним із нових композиційних матеріалів, які можна використовувати в медичних цілях – це геополімер, який є неорганічним полімерним матеріалом, що складається з алюмосилікатних джерел, таких як метакаолін і золь-гелевий синтезований матеріал та активатора лугу, що складається із сильного гідроксиду лугу та розчину силікату натрію. У цьому оглядовому дослідженні розглянуто сировину, лужні активатори та домішки для геополімерів, а також застосування матеріалу на основі геополімерів у медичних цілях. Також обговорюються перспективи та проблеми геополімерів для медицини. Регульована міцність і пористість роблять цей матеріал універсальним для покриття субстратів, щоб стати матеріалом кісткового каркасу. Проте залишається занепокоєння щодо вимивання та високої лужності геополімерів. Це можна покращити, зменшивши молярність гідроксиду натрію та змішавши геополімер із сполуками, щоб уловити шкідливий агент фільтрації всередині та вивчити різні розчини для активації геополімеру.

Ключові слова: антибактеріальна дія; біокераміка; доставка ліків; геополімер; медицина.