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Manufacturing Process and Benefits of Glass-Ceramics from Basalt Rocks

Syaipudin Anwar[1], Sugiyanto[1*], Irza Sukmana[2], Muhammad Hanif[3], Sudibyo[4], Yusup Hendronursito[4]

[1,2]Mechanichal Engineering Department, Engineering Faculty, University of Lampung,
Jl. Prof. Soemantri Brojonegoro, Bandar Lampung 35145
[3]Chemical Engineering Department, Engineering Faculty, University of Lampung,
Jl. Prof. Soemantri Brojonegoro, Bandar Lampung 35145
[4]Mining Technology Research Center - National Research and Innovation Agency,
Jl. Ir. Sutami KM. 15 Tanjung Bintang, South Lampung, 35361
**Corresponding author*: sugiyanto.1957@eng.unila.ac.id

Abstrak

As a means of promoting national independence, the growing usage of dental implants must be bolstered by the advancement of indigenous materials. Indonesia possesses many natural resources that could be utilized as a material for dental implants. Bioceramic materials, which include bioactive, bioresorbable, and bioinert materials, can be used for dental implants. Glass-ceramics from basalt rocks are currently regarded as one of the bioactive materials of interest. In this review article, various techniques for turning basalt into glass-ceramics are discussed. By using glass-ceramics from basalt rocks as a potential supply of dental implant materials, a country's independence and the welfare of its citizens will be supported.

Keywords: Glass-Ceramics, Biomaterials, Biomaterials Development.

1. Introduction

Dental implants are becoming more and more necessary to support orthodontic therapy and craniofacial reconstruction by replacing lost teeth and enhancing tooth structure. For dental implants, metals and alloys, polymers, and ceramics and carbon are the three primary categories of synthetic biomaterials [1]. Materials made of metal and alloys are preferred because of their extreme strength. Nonetheless, metal artificial bone requires special care when in use. Regarding metal materials, the three biggest risk factors are corrosion, biofilm formation, and hypersensitivity reactions. Nonetheless, osseointegrated dental implants continue to make extensive use of titanium and its alloys. Titanium hypersensitivity reactions continue to be confirmed in a large number of patients [2].

As a result, due to their superior biocompatibility and numerous advancements, ceramic and polymer materials are now used instead of metal in medical equipment [3]. For more than 20 years, bioceramics has been the focus of extensive research and clinical dentistry practice using innovative materials. Because of their chemical resemblance to human bone, several bioceramic formulations have been developed. Metal implants can be made more biocompatible by applying a covering made of bioceramics. It replaces the lost tissue by acting as an absorbable lattice. Bioceramics are strong, wear resistant, and have exceptional thermal and chemical stability [4].

Bioceramics are strong, non-toxic materials. Bioceramics can be liquid, absorbable, biodegradable, or interact with the tissues around them. Ceramics can bind to proteins and sugars. Blood arteries, for instance, have the ability to pierce through some bone and prosthetic ceramic materials and eventually replace them. Bioceramics is a unique biomedical substance.

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extensive research and clinical dentistry practice using innovative materials. Because of their chemical resemblance to human bone, several bioceramic formulations have been developed. Bioceramics are often used as a coating material to improve the biocompatibility of metal implants. It functions as an absorbable lattice to rebuild the replaced tissue.

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2. History of bioceramic development

The "Paris" plaster ($CaSO_4$, H_2O) was the subject of the first bioceramic study. Dressman released a report in 1892 detailing the first use of this plaster for mending bone injury. Moreover, tricalcium phosphate was effectively employed in 1920. Hulbert's work in the 1960s marked the beginning of the development of bioceramic materials. This was expanded further into the 1970s and 1980s [5]. Studies on the extremely low coefficient of friction between alumina and zirconia were carried out in 1977. According to historical records, between 1985 and 2001, 400,000 zirconia-made femoral heads were used in hip joints. As seen in Figure 1, the usage of bioceramic materials in dental implants is categorized [6].

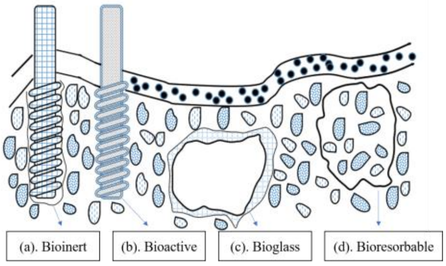

Figure 1. Classification of bioceramics according to their bioactivity [6].

In Figure 1 there are four types of body responses to implanted materials, which allow attachment of the material to the muscle: (a). bioinert (alumina dental implants); (b). bioactive (hydroxyapatite); (c). surface active (bioglass); and (d). bioresorbable (tri-calcium phosphate/Ca_3 (PO)).

Depending on how the tissue responds to the implant surface, the major categories of bioceramics are separated. Glass ceramics and bioglass are examples of bioactive materials. absorbable substances include hydroxyapatite (HAp) and calcium phosphate. Carbon, zirconia, and alumina are examples of bioinerts.

Bioinerts exhibit superior mechanical capabilities and a high degree of stability in vivo. Upon fusion with living bone tissue, the material will follow the osteogenetic contact pattern. Osteoconducting, bioactive ceramics have the ability to chemically attach to living bone. Bioactive ceramics often have a lower mechanical strength than bioinert ceramics [7]. On the other hand, a ceramic substance that is bioresorbable can break down when replaced by tissue that regenerates [8].

Several types of bioactive ceramics and glass ceramics have been developed. Glass-ceramics with different functions, such as superior mechanical properties and fast setting capability. Glass, which is the most widely used research in the implant field, is mainly based on silica (SiO_2) which may contain some other critical phases. The application of silicate ceramics (SiO_2-Na_2 O-CaO) that have at least 65% silica by weight. Although it is brittle, bioglass 45S5, which is composed of 45% SiO_2, 24.5% CaO, and 24.5% NaO, has been in use since 1971. Six percent P_2O_5 adds a significant boost in strength.

It has been reported that AW Glass Ceramics produces glass ceramics. These glass-ceramics contain oxy-fluor-apatite $Ca_{10}(PO)_{46}(OH,F_2)$ and wollastonite ($CaO.SiO_2$) in a MgO-CaO-SiO_2 glass matrix [9]. This glass ceramic spontaneously binds to living bone without the formation of surrounding fibrous tissue. Development of machine-fabricable bioactive glass with appetite phase and phlogopite has been carried out. Clinically used as a spine maker [6].

3. Basalt as a Glass-Ceramic Material

Glass ceramics made of basalt rocks were created in the early 1980s. Since 1977, the process of turning basalt rocks into glass-ceramics has been trademarked. According to the description, the process involves melting basalt rock and enriching it with SiO_2, CaO, and MgO in a certain ratio to create glass-ceramics. After the basalt is melted and cooled, hard glass-ceramic crystals are formed by thermal processes. An evaluation of additional studies examining the impact of basalt on living organisms has also been conducted. For six months, they studied the growth of basalt and asbestos fibers in mice [10]. When mice were given asbestos fibers, thirty-three percent of the mice perished, and when the mice were given 2.7 g/kg of asbestos, every mouse perished. All rats were able to survive at doses up to 10 g/kg when exposed to basalt fibers. Similarly, the experiment's analysis revealed that basalt exhibited a reaction that was safe for human health [11].

It has been done using local basalt from the Copaonic Mountain as a glass-ceramic material. A number of methods, including optical microscopy and X-ray phase analysis (X-RD), were used to study the formation phenomenon of glass crystallization. This study experimented with heat treatment and its impact on product attributes and microstructure control. Melting basalt rock in a ladle at a temperature between 1,250 and 1,300 degrees Celsius is the method of heat treatment used. crystallization through warming for three to eight hours at 950, 1,000, and 1,050 C. Phase formation observations yielded two crystal phases: Hypersthene ((Mg, Fe,) SiO_3) and Diopside $CaMg\ (SiO\ )_{32}$. The crystals that were created varied in size from 8 to 480 µm. Wear resistance ranges from 0.1 to 0.2 g/cm^2, microhardness from 6.5 to 7.5, and compressive strength from 2,000 to 6,300 kg/cm^2 [12].

Glass ceramics from basalt rocks are being developed because of their toughness and outstanding biocompatibility. They are typically produced as powders and applied as coatings or fillers in bioceramic composites to provide reinforcement. Glass-ceramic produced by heat treating basalt rock for 60, 120, 180, and 240 minutes at different temperatures of 800, 900, and 1.000 °C [13]. AISI 1040 is coated with glass-ceramic utilizing a plasma spray process. The goal of the plasma spray approach is to create oxide crystal-based ceramics that can be used to manufacture glasses. In order to create glass-ceramic, an amorphous glass structure must form prior to the crystallization heat treatment. The glass transition temperature (Tg) is estimated to be in an endothermic state of about 804 °C based on the DSC test results, and two exothermic peaks at 841 °C and 880 °C suggest crystal formation. Two distinct crystalline phases are thought to have formed after heat treatment, based on the appearance of two crystallization peaks on the DSC curve. The XRD examination revealed that the crystal phases augite $[(CaFeMg)\text{-}SiO_3]$, aluminum-diopside $[Ca(Mg,Al)(Si,Al)O_{26}]$, and diopside $[Ca(Mg_{0.15}\,Fe_{0.85})(SiO)_{32}]$ were produced by heat treatments of 800, 900, and 1.000 °C for two hours. The diopside-augite phase offers exceptional resistance to wear and chemicals. The absence of nucleating agents in glass ceramics manufactured from basalt rocks can be attributed to the existence of Fe oxidation. Fe undergoes oxidation to produce Fe O_{34}, a nucleating agent and site for crystal formation. The diopside-augite peak increases with increasing crystallization temperature, according to X-ray defragment analysis. Numerous crystalline phases form in the glass as a result of the heat treatment temperature.

Numerous studies on the safety and body's resistance to artificial materials implanted have examined the usage of glass-ceramic basalt as a reinforcing filler in HAp composites against potential hazards of use in the human body. Basalt has even been traded extensively for usage in the medicinal field. Service-disabled veteran-owned small businesses (SDVOSBs) produce advanced materials. The basalt is one of them. It is untrue to say that basalt products are neither combustible or explosive when they come into contact with water or air. Basalt does not react chemically with other substances in a way that could endanger human health or the environment [14]. Powdered basalt (BS) is completely stable both chemically and physically in the living environment. Composites of HAp powder containing 5 and 10% by weight of basalt were shown to be safe in this investigation. After the powder had been agitated and compressed, the sintering procedure was completed. The temperatures that were chosen for sintering were 700, 900, and 1,200 °C.

The biological fluid environment is 0.9% NaCl solution at pH 6.7; Ringer's solution (NaCl; and KCl; and $CaCl_2$); Ringer - Locke solution (NaCl; $NaHCO_3$ $CaCl_2$; KCl; and glucose). The X phase lines that are a component of the BS become more visible when the annealing temperature is raised to 900°C and the BS concentration is increased to 10%. The HAp composite system interacts nearly identically with 5 and 10% BS. Given its strength properties, it has been demonstrated that the HAp + 10% BS composite system, at a sinter temperature of 900°C, is a potential material for reconstructive surgery. Nearly identical to the natural characteristics of bone, hardness is 0.86 GPa Hv and modulus of elasticity is 23.7 GPa. According to the study, BS is safe for an organism's living environment [15]. The inclusion of 5% and 10% basalt powder as filler enhanced the physical and mechanical qualities of HAp products, according to research on the mechanical and physical testing of basalt powder-reinforced HAp composites. The formation of β-TCP phase occurs at low temperatures. It is thought that the β-TCP phase forms more biocompatible than the α-TCP phase. The potential to modify the HAP - β-TCP ratio holds great promise for generating materials possessing bioresorbable qualities. When 5% basalt was added to HAp, the highest compressive strength that was suitable for HAp-BS composites was achieved; however, the strength reduced when 10% basalt was added [16]. The mechanical and physical qualities of glass-ceramic materials can be enhanced by their development and production from raw materials. Furthermore, this approach plays a significant role in the narrative of the modern world [15].

4. Glass-Ceramics

In general, materials can be categorized as crystalline or amorphous based on how their atoms are dispersed in respect to their structure. Crystalline materials possess a long-range structural order because their atoms are arranged in a periodic manner throughout their structure. On the other hand, atoms in amorphous materials are dispersed randomly over space and lack long-range organization [21, 22]. Eyeglasses are a common example of an amorphous material. W.H. Zachariasen [23] presented a set of guidelines in 1932 that are satisfied when a substance makes glass. According to his criteria, glass atoms should be arranged in a three-dimensional network without any long-term order.

Glass-ceramic materials are characterized as ceramic materials in which the crystalline phase is developed by controlled glass nucleation and crystallization. They are created by combining the two types of structures that have been presented (amorphous and crystalline). Fine-grained crystals with various orientations can form in the glass matrix through effective nucleation [24, 25]. The crystalline phase makes for 50–95% of the volume in the microstructure of glass-ceramics.

Glass that has been heat treated may form one or more crystalline phases. There will be a change in the composition of the produced phase and the residual glass compared to the original glass [25, 26].

Crystal growth and nucleation Tammann established the fundamentals of regulating glass crystallization in 1903, but the general theory of nucleation and crystal growth was not unified until the 1960s and 1980s. Two processes are needed to convert glass into glass-ceramics: nucleation, or the production of crystal embryos, and crystal growth, which is a thermal and kinetic process that yields an ordered structure from an amorphous system [24, 27]. The combination of these two processes crystallization and nucleation is referred to as crystallization [28]. The term "deviation" [27] is another term used in the literature to characterize this occurrence.

Without regulated crystallization of the basic glass, it is impossible to produce glass-ceramic materials with unique features, and nucleation is a critical stage in this process [17,18,29]. There are two possible processes for the nucleation of the crystalline phase: homogeneous nucleation and heterogeneous nucleation [17,18,30,31].

Every site at the liquid cooling point experiences random nuclei production in the homogeneous nucleation process [32,16]. Thermodynamically, nucleation in glass will happen at a lower temperature when atomic clustering is regular enough to allow crystal embryos to form. The development of these embryos suggests a decrease in the system's free energy. The embryo must, however, be equal to or greater than the critical radius value for it to be stable in the melt. This value is determined by the crystallization energy and surface tension at the crystal fusion interface [30, 28].

Nuclei are created from impurities or pre-existing interfacial surfaces in heterogeneous nucleation processes (liquid air, liquid container walls). Stated differently, these surfaces operate as catalysts, promoting the process of nucleation and crystallization [17, 18, 32].

In contrast to heterogeneous nucleation, homogeneous nucleation occurs less frequently. Surface heterogeneity typically acts as the nucleator of crystallization in glass. On the other hand, crystals must develop both inside and on the material's surface in order to produce glass and ceramics. To induce and/or speed up the crystallization process and produce discontinuities in the glass structure, nucleating chemicals are therefore added to the glass mixture in trace amounts [25,18].

Oxides are the primary nucleating agents. There are two types of oxides: P_2O_5 and TiO_2, which function through an imbalanced charge mechanism, and Cr_2O_3, which works through a valence change mechanism. Metal colloids (Pt, Ag, and Cu) are additional nucleating agents that can precipitate metal species via photosensitive or redox processes [25, 27, 32].

The crystal development stage follows the production of stable nuclei within the glass. From a kinetic perspective, the development is shown by two distinct curves: the nucleation and crystal growth as a function of temperature [32]. The temperature and the ease with which atoms migrate along the lattice will determine the rate of crystal formation [20].

At very low temperatures, growth will not be preferred as the atoms will not have enough energy to go along the structure. Similar to this, development will likewise be sluggish at extremely high temperatures because of the system's difficulties releasing the heat generated by crystallization. Because heat will disperse more readily at these temperatures, growth will be encouraged and the nucleation and crystal growth curves have peaks where the rate will be maximal [33].

The temperature at which the nucleation rate and crystal growth are maximal is shown in Figure 2 by T_{Nmax} and T_{Cmax}. The purple region denotes the ideal temperature range for creating glass ceramics and correlates to where the curves intersect. The nucleation and crystal growth processes should take place in two stages if T_{Nmax} and T_{Cmax} are widely separated, that is, if the curves do not overlap. On the other hand, the nucleation and crystal growth processes happen simultaneously and the creation of glass-ceramic materials can be completed in a single phase if T_{Nmax} and T_{Cmax} are close and the curves overlap [17,27, 32].

Properties and raw materials The ability to create a variety of microstructures with unique qualities that are connected to the mix of amorphous and crystalline phase properties is one of the main benefits of glass-ceramic materials.

To facilitate the nucleation and growth of crystals, the proper chemical composition and heat treatment cycle must be chosen in order to produce a variety of microstructures [18].

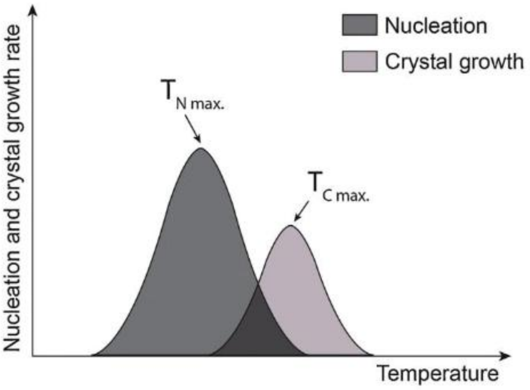

Figure 2. Crystal nucleation and growth curves. Where T_{Nmax} and T_{cmax} represent the temperature at which the nucleation rate and crystal growth are maximum, The purple area corresponds to the overlapping curves.

The glass-ceramic material's composition needs to be conducive to glass production, which permits controlled crystallization. Certain mixtures crystallize very fast and spontaneously, whereas other compositions generate very stable glasses that impede the crystallization process. Glass and a thermodynamically stable mixture of crystals regulated by phase equilibrium principles can generate metastable crystals under ideal compositions [19].

Glass-ceramics can be categorized as alkali and alkaline earth silicates, aluminosilicates, fluorosilicates, silicon phosphates, iron silicates, and phosphates depending on their chemical makeup, according to Holand and Beall [18]. Basalt glass and ceramics are examples of iron silicates. Products made from fused rocks are widely used and regarded as antecedents of glass and ceramics [19].

Because these materials can combine the special qualities associated with the amorphous structure of glass with the distinctive attributes of ceramics (crystalline phase), they offer an unexpected range of characteristic combinations. Density, hardness, chemical resistance, and wear are examples of glass-ceramic properties that are primarily dependent on the crystalline phase's good dispersion within the glass matrix [20].

The best glass-ceramic materials typically have a structure that has more than 90% crystalline phase, with crystal sizes ranging from 0.5 to 1 m [21]. Because it's a ceramic material, the final product's qualities will be greatly influenced by the surface finish and residual porosity.

The aerospace industry created the first commercial glass-ceramic materials in the late 1950s to make domes to shield internal radars in rocket and airplane noses. The materials exhibit low dielectric loss, low coefficient of thermal expansion, strong abrasion resistance, and an extremely low and homogeneous dielectric constant [18].

With time, additional uses for glass-ceramics have surfaced, including:

- Technical applications: genuine photosensitive glass-ceramic pairings that can be scratched. Corning's lithium disilicate glass ceramic, known as Fotoceram®, is an illustration of this kind of material. Equipment for the electrical and micromechanical sectors is made from this substance. Another illustration is the glass ceramic Foturan®, which is produced by Schott AG in Germany and is utilized in headphone acoustic systems, integrated micro-optics and optical systems, inkjet printheads, pressure sensor substrates, and precision automobile engineering [18].

- Applications for consumers: In 1959, Dr. Stookey created the first glass ceramic product in history, which was sold as home appliances. Pyroceram 9608 was the name of this substance (Corning Glass

Works). New consumer applications have surfaced over time, such as the well-known cooktop. The Eurokera® cooktop, which is currently available for purchase internationally, serves as one illustration [22].

Medical and dental applications: Biocompatible glass ceramic materials can be broadly divided into two groups for medical applications, which vary in the properties and the environment in which they are used: restorative dentistry (materials used to restore natural teeth without requiring an insertion into the human body) and implantology (prostheses implanted inside the human body, including implanted teeth and roots) [24,20]. Furthermore, biocompatible glass-ceramics have potential in the fields of tissue engineering and bone regeneration, according to recent studies [23, 34]. In a recent assessment of the primary characteristics and uses of bioactive glass ceramics, Montazerian and Zanotto [25] offered ideas for further development and advancement of these materials.

Waste recycling applications: In the majority of industrial processes, byproducts are created. The volume of by-products is growing as a result of the industrial sector's expansion, which creates ongoing concerns about how to properly dispose of these waste. Reusing industrial waste is a practical and efficient way to lessen its influence on the environment. In this regard, a number of researches have been carried out with the intention of recycling leftovers to create glass and ceramics. A review study on the creation of glass ceramic materials from garbage was published by Rawlings et al. [26]. This study describes various processing techniques for producing these materials from silicate waste, such as steel slag, fly ash, coal combustion ash, hydrometallurgical sludge, shattered glass, or combinations. Karamanov et al. [27] produced glass-ceramic materials by a sintered crystallization method using ash from a solid waste incinerator. Khater et al. [28] created various compositions with waste from granite quarries among other ingredients to produce technical glass ceramics at a reasonable cost of manufacture. They discovered that the resultant glass ceramics are very abrasion resistant and strong, offering them as an alternative for uses involving harsh mechanical conditions.

Apart from the issue of reusing garbage, there is an ongoing quest for new substitutes made of environmentally safe materials. Basalt is abundant and an environmentally benign natural stone that can be utilized as a raw material for the creation of glass ceramics. The next topic addresses the manufacturing of glass and ceramics from basaltic rocks in this context.

5. Glass-Ceramics Basalt

George H. Beall and Hermann L. Rittler filed the first patent for glass ceramic materials made from basaltic rocks in 1971 with the title "Process for forming basaltic glass ceramic products" [35]. The process described in the invention involves melting basalt under oxidizing circumstances, quickly chilling the resulting glass, and then applying heat to the glass matrix to create uniformly distributed crystals. The production of glass-ceramics using natural raw materials is highly significant from an economic, technological, and scientific standpoint. Different types of rocks can be utilized to create glass ceramics with the right chemical composition, leading to a wide range of microstructures and technological features [36]. To achieve the correct microstructure, control over the heat treatment's duration and temperature is crucial. The resulting microstructure is thinner the higher the glass's capacity for crystallization and the slower the pace of crystal development. Controlling the raw materials is another crucial aspect of processing, since they are typically derived from rocks and lack adequate mineral, physical, and compositional homogeneity, which directly affects the properties of the finished product [20].

Table 1. Chemical Composition (weight %) of basalt from different regions of the world

Oxide (wt. %)	Typical Basalt, [29]	Yusup Hendronursito, Indonesia [71]	Thrace Region, Turkey [36]	Southern Anatomi, Turkey [37]	Arkhangelsk Oblast, Russia [38]	SGF, Brazil [39]	Vrelo-Kopaonik, Serbia [40]	Vrelo Kopaonik, Serbia [41]	Egyptian Basalt, Egypt [42]
SiO_2	48.3	48.618	45.91	43.18	45.83	51.42	56.21	49.33	48.39
Al_2O_3	13.03	18.837	12.16	13.15	15.34	13.81	18.61	16.13	13.98
Fe_2O_3	6.84	12.783	10.74	13.49	1.52	7.36	1.15	3.81	12.63
FeO	7.72	-	-	-	9.16	5.83	2.97	2.68	-
CaO	10.91	9.532	9.12	9.67	7.72	10.45	7.78	8.87	9.16
MgO	5.46	-	12.16	8.48	6.78	6.29	3.4	6.48	6.92
K_2O	0.51	0.618	4.25	2.78	1.33	0.7	3.37	2.7	0.79
Na_2O	2.34	3.061	-	4.27	3.37	2.45	4.73	3.3	2.5
TiO_2	2.59	1.277	2.93	3.34	4.73	1.37	1.11	1.94	-
MnO	0.23	0.204	-	-	1.11	0.2	-	0.14	-
P_2O_5	0.26	-	-	0.96	-	0.14	-	-	-
H_2O	1.42	-	-	-	-	-	-	1.57	-
CO_2	0.49	-	-	-	-	-	-	-	-
LOIc	-	-	2.72	-	-	-	-	-	5.32

In comparison to other rocks, volcanic rocks have a superior chemical composition consistency and analogical homogeneity of miners, which makes them easier to process. This justifies the preference for utilizing igneous rocks in the creation of glass ceramics. Because of its easier production procedure and lower melting temperature, basaltic rock is the most favored type of igneous rock [21].

At roughly 1500°C, basalt melts readily. It will turn into glass if it cools quickly. If the ratio of Fe^{3+} to Fe^{2+} oxides in the rock composition is larger than 0.5, Holand and Beall [18] state that glass-ceramic materials can be produced by thermally processing this glass. The clustering of iron oxides in the glass structure is thought to play a role in crystal nucleation. When heated to temperatures between 650 and 800 ℃, iron reacts with oxygen to form magnetite ($FeO\ Fe_2O_3$), the first phase to crystallize and an agent that acts as a nucleating agent to start crystallization. The phase development, pace of crystallization, and ultimate characteristics of the glass-ceramic are also influenced by the ratio of iron's oxidation state [19].

Since the majority of ceramics are oxides, changes in temperature and pressure can affect the valence of cations, making the partial pressure of oxygen, or pO_2, a crucial variable in the production of these materials. The valence of a polyvalent cation, like iron, is contingent upon its oxygen activity, which is exactly proportional to its partial pressure [37].

Glass-ceramic processing Volume crystallization, sintered crystallization, and final processing are the three primary methods used to prepare glass-ceramic materials [24, 27]. Processes for volume crystallization and sintered crystallization include first producing glass and then heat-treating it to encourage the creation of crystals in its structure. This is known as the "conventional method" of producing glass ceramics. The material is melted in the petrurgical processing procedure, and the suitable crystalline phase can precipitate by carefully regulated cooling [38].

A proper mixture of raw materials is melted and poured into a mold to manufacture glass in the volume crystallization processing route. In order to encourage crystallization through the processes of internal nucleation and crystal growth, this glass is then given a unique heat treatment. In this instance, nucleation from the molten glass happens uniformly, with random nuclei forming at every liquid point [24, 28]. Nucleating chemicals are frequently used in this kind of processing to encourage and/or speed up the crystallization process [39].

However, the starting material for the sinter-crystallization processing route is ground glass powder. The powder is created by standard methods (such as pressing, collage, or injection) and then undergoes a particular heat treatment that combines the crystallization and sintering processes. Here, low surface energy locations (substrates) where crystals develop are the heterogeneous sites from which nucleation occurs [40]. The powder's surface flaws serve as nucleation sites [18].

Alternatively, petrurgical methods can be used to obtain glass ceramics. In this instance, a heat treatment that is akin to the spontaneous process of mineral formation is used; that is, the molten material nucleates and crystallizes through a gradual, regulated cooling from a high temperature to room temperature. Primary crystallization is the term for this process [20,17,26]. The TTT diagram or a time-temperature-transformation gram diameter indicates that nucleation and development of specific crystalline phases might happen throughout the gradual cooling process [41]. The ability of the atomic structure to arrange itself into a stable crystal structure will determine the crystallization in this process [20, 21]. The original chemical makeup of the rock and glass used in this production process must facilitate the creation of a melt that can crystallize phases with simple isomorphic replacement.

The petrurgical approach is typically used in the production of glass-ceramics from industrial wastes like fly ash and blast furnace slag as well as natural raw materials like rocks and minerals. These materials have a significant propensity to crystallize because they melt quickly and alter viscosity over a small temperature range [20].

The "Silceram" process, which was created in the 1970s at Imperial College in London to produce inexpensive glass ceramics from blast furnace slag, is comparable to the petrurgical method. The "Silceram" method for crystallization involves a plateau during cooling at a particular temperature [41].

Similar techniques have been used in the research of Cocic et al. [53] and Matovic et al. [41] to produce glass ceramics with basaltic compositions using cooling crystallization isotherms.

When compared to traditional glass and ceramic processing processes, both petrurgical and Silceram processing procedures are more cost-effective. In order to encourage crystal nucleation and growth, conventional procedures, as observed, entail heating the base glass at two temperature levels, which increases the energy cost of the operation [26,41].

Glass-ceramics were obtained for basaltic compositions by Vicente-Mingarro et al. [28] using both conventional and petrurgical processes. The heat treatment cycle via the petrurgical approach begins with melting the rock at 1450 degrees Celsius, which is then regulated to cool at a rate of 5 degrees Celsius per minute to 850 degrees Celsius, and air cooling is the last step. Pyroxene and plagioclase, the two principal phases in this instance, exhibit eutectic-type primary weeping counting in the microstructure that has evolved. Conversely, in the traditional method, the glass underwent a heat treatment cycle to facilitate the secondary crystallization of the basalt glass. For phase nucleation, the glass is heated to 650 degrees Celsius for two hours. For crystal growth, it is then heated to 800 degrees Celsius for sixteen hours. In the primary pyroxene phase, homogenous crystallization takes place.

Characteristics and uses. Numerous scientific investigations have verified that basaltic rocks may be utilized to produce glass ceramics, and that other processing techniques and heat treatments are also viable.

The kinetics of basalt glass crystallization were assessed by Yilmaz et al. [42]. Fused basaltic rocks from Turkey's Thrace region were used to make the samples. They deduced that the diopside phase crystallizes at 788 °C, whereas the augite phase crystallizes at 845 °C. The resulting glass-ceramics feature a microstructure that is remarkably uniform, with finely scattered crystals.

The sinter-crystallization method was utilized by Karamanov et al. [43] to produce glass pottery from southern Anatolian basaltic rocks. The behavior of sintered glass and its crystallization in air and nitrogen environments were examined. The study's authors discovered that while intense crystallization processes in both atmospheres cause densification to decrease at low temperatures, oxidation of FeO occurs in air at increasing sintering temperatures, resulting in a 15-20% reduction in the formation of crystalline phases when compared to nitrogen atmospheres.

Alkaline basaltic rocks have the potential to yield ceramic materials, as demonstrated by Karamanov et al. [44]. After the stone was ground, the powder was compressed. The samples underwent heat treatment at temperatures between 1000 and 1140 °C. After being treated at 1000 °C, the material had a microstructure resembling glass ceramic, 0% water absorption, and degree 9% closed porosity. With a crystallinity index of degree 60% and the development of several phases (pyroxene, anorthite, spinel, and hematite), the composition positions utilized indicate a strong inclination to crystallize. It is possible to generate materials with good qualities, including an elastic modulus of 90 GPa and a flexural strength of 100 MPa, even using a low-cost production cycle. Generally speaking, commercial soda-lime-silica glasses have an elastic modulus of 70–75 GPa [28].

The hardness dependence of basalt glass ceramics with respect to heat treatment temperature was assessed by Jensen et al. [45]. Glasses treated at temperatures of 730, 850, 875, 900, 925, 937, 950, 1010, 1030, 1060, and 1084 °C were produced for the investigation using basaltic compositions. By using a force of 0.98 N for five seconds during micro-indentation, Vickers hardness was determined. The primary phase was determined to be augite crystals, and it was discovered that the hardness of the glass reduced in proportion to the sample's degree of crystallization. Samples with a degree of crystallization between 0.61 and 0.85 (corresponding to a heat treatment between 900 and 937 degrees centigrade) yielded the greatest hardness of 8.5 GPa.

The impact of iron content on the sinter behavior of basalt compositions was assessed by Drobot et al. [46]. Magnetic separation was used to separate the pulverized basalt into components that were magnetically deficient and enriched. The material can be utilized as a protective coating against acidic media, and the authors discovered that samples made by sintering non-magnetic components have higher hardness and acid resistance. However, magnetic components can be used to produce materials that are dominated by pyroxene, which is a necessary step in the process of producing high-quality feedstock for petrography.

Glass was created by Klein et al. [47] using basaltic rocks from Brazil's Serra Geral Formation, and they assessed the kinetics of magnetite crystallization without the use of nucleating agents. According to the study's findings, 650 °Cwas the greatest magnetite nucleation rate. Agate crystallized in its second phase after being heated to 860 °C. Ultimately, they discovered that the glass with the finest mechanical qualities was treated for 0.5 hours at 650 °C and subsequently for 1 hour at 860 °C. The resulting glass-ceramics had a uniform microstructure, finely scattered crystals, high hardness (8.18 GPa), and a respectable defense against NaOH acid attack.

Glass was prepared by Lima et al. [48] using basalt from the Serra Geral Formation (Brazil), and glass-ceramics were then made using a process of sintered crystallization. In an inert atmosphere, several heat treatments were applied. With the longest heat treatment (6.5 h), the bulk density, hardness, and crystallinity index exhibited the maximum values at 2.39 g/cm°C, 74.8%, and 9.81 GPa, respectively. The results also showed that these parameters increased with treatment time up to the final temperature. Comparable values, however, were obtained with a shorter heat treatment (2.5 hours) at the same end temperature (2.38 g/cm°C, 72.3%, and 9.68 GPa, respectively). As a result, the microstructure is unaffected by the isothermal step at the intermediate crystallization temperature.

The wear characteristics of glass ceramics made of basalt have been assessed in a number of research. Because of their great heat and chemical resistance, basalt glass ceramics have found extensive use in various industrial applications, particularly as coatings for solid particle and slurry transportation systems. Studying the eroding wear behavior is crucial because of this.

Mount Vrelo-Kopaonik (Serbia) olivine-pyroxene of basalt-based glass ceramics were manufactured and their wear was assessed by Pavlovic et al. [40]. We tracked the samples' mass loss as a function of cavitation time. The material can be used in situations where high cavitation loads are anticipated because of its strong resistance to cavitation wear, according to the results.

The erosive wear resistance of commercial basalt glass ceramics and its correlation with the impact angle of solid particles were evaluated by Öztürk et al. [49]. The impact angles of 30°, 45°, 60°, 75°, and 90° were employed. They came to the conclusion that there is a high correlation between the impact angle and the wear rate, and that the wear and damage process may vary depending on the impact angle. Erosive particles cannot produce a severe wear effect at a low impact angle of 30° because the glass-ceramic cannot completely absorb their kinetic energy. More energy travels through the surface and more material is lost as the impact angle (90°) rises. Greater wear effects, such as friction, are seen at moderate impact angles (45°, 60°, and 75°).

Furthermore, workable glass ceramics made from basaltic compositions may be produced as a substitute for commercially available workable glass ceramics, according to recent investigations. The machinability of glass ceramics is attributed to the fluorine and potassium phases, which is why Ercenk et al. [50] added MgF_2 and K_2O to the basalt formulation. Compositions including 80, 85, and 90% basalt were synthesized along with MgF_2 and K_2O. The findings demonstrated that machining performance improved at lower basalt contents (80%) and demonstrated the feasibility of producing glass ceramics that can be machined from basalt.

The thermal, electrical, and physical characteristics of glasses and glass-ceramics made of basalt compositions were assessed in a very recent study. Six glass compositions were created by Khater et al. [51] using basaltic rocks and incremental additions.

The findings of [37] demonstrate that the glass transition temperature (Ts) is between 737 and 711.6 °C, the coefficient of thermal expansion is 59.76×10^{-7} °C^{-1}, and the starting point and ranges of Ts are 668.79 and 632.34 °C, respectively. With an increase in cement dust content, flexural strength and Vickers microhardness both gradually decreased, going from 118 to 56 MPa and 6120 to 4020 MPa, respectively. In contrast to the mechanical performance, when the cement dust content increased, the density rose from 2.79 to 2.96 g/cm^3. The ideal specimens for the electronic enclosure business, according to the authors, are those that contain 90% basalt and 10% cement dust.

In comparison to glass and synthetic glass ceramics, Table 2 summarizes the characteristics of a few basaltic and basaltic-based glass ceramics. necessary [42]. Basaltic glass ceramics are an alternative to traditional, commonly used materials, such metals, utilized for coatings since they can be made from inexpensive raw materials and have great characteristics. Additionally, they are a great coating material for cast iron pipes used in the chemical industry to transport corrosive liquids because of their long-term chemical stability characteristics [20,21]. Because of their strong chemical resistance, the earliest glass-ceramics made from basaltic rocks were employed to enclose hazardous waste [36,52].

Basaltic rocks are now widely employed in Asian and European nations to make a wide range of goods, such as coatings, yarns, textiles, rods, and fibers. Since 1987, the Pune, India-based business Demech [53] has been utilizing basalt products. Coated pipes are its principal product. They claim that basalt has strong abrasion and corrosion resistance along with exceptional chemical resistance. The company uses a selective extraction method for its processing, followed by a melting process at 1500 degrees Celsius and molding into molds or centrifugation in cylindrical tubes. Finally, the pieces undergo a heat treatment cycle to induce basalt crystallization.

The Kalenborn firm [54] produces cast basalt products under the ABRESIST name that are used globally to provide dependable protection for steel industrial installation components and pipes in thermal power plants against frictional wear. The company claims that their cast basalt products offer great protection against abrasive wear due to their low coefficient of friction. Basalt products are made by the Czech [55], which makes lining pipes and tiles for sewage systems. In comparison to ceramic tiles, Table 3 displays a few of the physical characteristics of commercial basalt glass ceramics. More recent research has indicated that glass ceramics based on basalt may find use as fuel cell sealants. A solid oxide fuel cell (SOFC) is a device that uses an oxidant and fuel to undergo a redox reaction to transform chemical energy into electrical energy. It's a "clean" method of producing energy [56]. Glass-ceramics were created by Ercenk et al. [57] using a composition based on basalt as a sealant material for SOFCs. To the basalt, they added SiO_2, Na_2O, CaO, MgO, and B_2O_3. The mixture of thermal and mechanical waste cement in the sealing material should range from 10 to 50 weight percent.

The glass transition temperature (Tg) and glass softening temperature (Ts), which are used to assess the glass's flow characteristics, are significant factors for this material. Therefore, high Tg and low Ts are needed in order to prevent interfacial breaking at working temperature. According to the findings, the material for the basalt glass-ceramic sealant has potential qualities for usage in SOFCs. Additives caused basalt's softening temperature to drop from 1184 ℃ to 956 ℃. It might not be sufficient for adequate wetting and bonding, though. As a result, complementary research must be done.

Because of their dielectric characteristics, basaltic glass-ceramic materials may find use as semiconductors and insulators, according to another study. The findings indicate that low dielectric materials in the electronic enclosure industry can be made from basalt glass ceramics [58].

Table 2. Summary of properties of some basalt and basalt-based glass-ceramics compared to glass and synthetics.

Composition	Method	Heat Treatment (Temp & time)	Main Crystalline Phases	Hardness	Density (g/cm^3)	Referensi
Glass						
Borosilicate glass (SiO2–Al2O3–B2O3–Na2O)	-	-	-	4.1 GPa	2.4	[61]
Synthetic glass-ceramic MACOR® – Machinable glass-ceramics (55% fluorphlogopite mica and 45% borosilicate glass)	-	-	-	250 kg/mm^2	2.52	[62]
Basaltic rock from Serra Geral Formation, Serra Gaúcha, Brazil	Sinter Crystallization (air)	1032 ℃, 0.5 h	Magnetite, augite, albite, and quartz	9.81 GPa	2.39	[39]
Basaltic rock from Serra Geral Formation, Serra Gaúcha, Brazil	Bulk crystallization (air)	860 ℃, 1 h	Magnetite and augite	8.18 GPa	-	[57]
Basaltic rock from East Lampung, Indonesia	Sinter Crystallization (air)	1050 ℃, 8 h	Anorthite, Pyroxene, Olivine	8.3 GPa	2.64	[72]
Basaltic rock from Northwest Harrat Rahat, Saudi Arabia	Bulk crystallization (air)	1000 ℃, 2 h	Augite, olivine, hematite, and magnetite	7.04 GPa	2.98	[63]
Alkaline-olivine tuffs from Southern Anatolia, Turkey	Sinter Crystallization (air)	1100 ℃, 1 h	Pyroxene, plagioclases, olivine, spinel, and hematite	-	2.66	[37]
Basalt rock from the Vrelo, Serbia	Petrurgy (air)	950 ℃, 3 h	Pyroxene (diopside, hypersthene)	7.2 Mohs' Scale	-	[41]
Basaltic-based glass-ceramic						
Sinai basaltic rocks (70 wt%) with by-pass cement dust (30 wt%)	Bulk crystallization (air)	1000 ℃, 2 h	Diopside, anorthite, magnetite, and gehlenite	4.8 GPa	2.96	[64]
Basaltic rocks (80 wt%) and ceramic (20 wt%) waste	Bulk crystallization (air)	900 ℃, 2 h	Augite, magnetite, and olivine	5.58 Gpa	-	[65]

Table 3. The physical properties of commercial basalt glass-ceramics are compared to (alumina) ceramics.

Material	Density (g/cm^3)	Compressive Strength (kg/cm^2)	Hardness (MΩ)	Abrasion Resistance (cm^3/ 50 cm^2)	Company
Lining pipes of cast basalt	2.9 – 3.1	min. 4500	8	-	Demech [67]
Tiles of cast basalt	2.9 – 3.0	3000 – 4500	8	Max. 5	Eutit [69]
Tiles of cast basalt	2.9 – 3.1	3001 – 4500	8	5	Matas [70]
Ceramic tiles (alumina)	3.0 – 3.7	min. 4500	9	-	Demech [67]

A number of studies have suggested that basalt glass ceramics coated on steel could be used to increase the materials' resistance to heat, oxidation, wear, corrosion, and erosion. After applying a plasma spray to coat the metal with basalt powder, a heat treatment procedure is used to cause crystallization. Research demonstrates encouraging and satisfying outcomes (see, for instance, [59–61] and the references therein).

Due to their intriguing qualities, basaltic rocks have also attracted a lot of technological interest in their potential applications for producing fiber. These fibers are inorganic, non-toxic, natural, inexpensive, and have great mechanical strength, high temperature resistance, outstanding chemical stability, and ease of processing [62, 63]. Usually, they have just as much as or more than glass fiber. Some fibers have the following modulus of elasticity (GPa): basalt fiber, 95-115; aramid fiber (1414), 124-130; E glass fiber, 73-78; S glass fiber, 83; and carbon fiber (T300), 230-240 [64]. Metal using a plasma spraying technique, followed by a heat treatment procedure to crystallize it.

Melting basaltic rock at 1400 degrees Celsius produces fiber. To create continuous basalt fibers, the melt is extruded through a platinum-rhodium die under hydrostatic pressure. Depending on the application, cutting machines are used to cut the fibers to the appropriate length. The fiber's measurements fall between 10 and 20 micrometers for diameter and 3 and 130 mm for length. The primary benefit of basalt fibers over carbon and glass fibers is their lower production costs and energy consumption [62, 65]. Basalt fibers are primarily used in the creation of composite materials. In civil engineering, the fibers are primarily utilized as reinforcement for concrete [62,63,65-68]. Furthermore, basalt fibers are utilized in the production of superior, lighter hybrid composite materials (i.e., materials containing two or more fiber types in a single matrix) for use in infrastructure applications [69]. The oxidation and crystallization of basalt fibers at temperatures exceeding approximately 300 degrees centigrade poses a constraint on their use in structural polymer matrix composites. The fibers become more brittle as a result of these surface and microstructural alterations, which reduces their tensile strength [70-72].

6. Conclusion

Potential natural resources from Lampung Province exist that could be utilized as dental implant material, particularly in the form of basalt stone. Despite being mostly used as building material today, basalt rock has a bright future in the field of dental implants. For dental implant applications, basalt rock from the Sukadana region and other parts of the province can be utilized as a glass-ceramic material. But more work is required to fully realize this potential, particularly in the area of glass-ceramics-based research on basalt stone's potential as an implant material. Furthermore, basalt can be made into glass-ceramics with a variety of microstructures by heat treatment and chemical composition changes. This allows for applications in a number of industries, including biomaterials, fibers, textiles, and special applications like fuel cell, insulator, and semiconductor manufacturing.

Reference

[1] Meffert R M, Langer B, Fritz M E 1992 Jurnal periodontologi. 63 859-870.

[2] Přikrylová J, Procházková J, Podzimek Š 2019 Penelitian BioMed internasional. 2519205

[3] Fitriani C Y, Wibawa A 2019 Insisiva Dent. J.: Majalah Kedokteran Gigi Insisiva. 8 53-58.

[4] Jayaswal G P, Dange S P, Khalikar A N 2010 The J. of Indian Prosthodontic Soc.10 8-12.

[5] Hench L L 1991 J. of the american cer. Soc. 74 1487-1510.

[6] Heness G, Ben-Nissan B 2004 Forum bahan 27 104 114

[7] Yamamuro T 1990 Buku Pegangan Keramik Bioaktif (Florida: CRC Press Boca Ranton)

[8] Patel N, Piyush G A 2012 Int. J. Teknologi Berkembang. Adv. Eng. 2 2250-2459.

[9] Kokubo T, Soga W, Kato A 1991 J. Ceramic. Soc. 1991 21 500-518

[10] Kogan F, Nikitina O 1994 Perspektif. 102 205-206.

[11] Mcconnell E, Kamstrup O, Musselman R, Hesterberg T, Chevalier J, Miller W, Thevenas P 1994 Toxicol 6 571-614.

[12] Matovic B, Boskovic S, Logar M 2003 J. Srb.Chem.Soc 68 505-510.

[13] Yilmaz S, Bayrak G, Sen S, Sen 2006 Bahan 27 1092-1096.

[14] Sdvosb Https://Www.Reade.Com/Produk/Produk/Serat-Batu-Basalt-Serbuk

[15] Boshytska N V, Fedorenko Y O, Rekos A O, Kaplunenko N V 2017 Serbuk Logam. Met. Ceram. 55, 574-579.

[16] Kaplunenko N V, Ulyanchych N V dan Klipov V D 2016 Metalurgi Serbuk dan Keramik Logam 55 306-311.

[17] Shelby, J.E. Introduction to Glass Science and Technology, 2nd ed.; The Royal Society of Chemistry: Cambridge, 2005.

[18] Holand, W.; Beall, G.H. Glass-ceramic Technology, 2nd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, 2012.

[19] McMillan, P.W. The crystallisation of glasses. J. Non-Cryst. Solids 1982, 52, 67-76. doi: 10.1016/0022-3093(82)90281-2.

[20] Strnad, Z. Glass and Ceramics Materials; Elsevier: Amsterdam, 1991.

[21] Gill, R. Modern Analytical Geochemistry; Taylor & Francis: London, 1997.

[22] Hernandez Santana, T. Estudio de la cristalización en vidrios obtenidos a partir de rocas basálticas canarias. Ph.D. Thesis, Departamento de Petrología y Geoquímica, Universidad Complutense de Madrid, Madrid, Spain, 1992.

[23] Mauro, J.; Deubener, J.; Hommerich, E.F.Y.; Hench, L.L.; Brow, R.C. Glass and Glass-Ceramic Durability and Their Use in Nuclear Waste Management. J. Non-Cryst. Solids 2017, 471, 490-495. doi: 10.1016/j.jnoncrysol.2017.05.019.

[24] Shackelford, J. Introduction to Materials Science for Engineers, 8th ed.; Pearson Higher Education, Inc.: Upper Saddle River, NJ, 2014.

[25] Zachariasen, W.H. The atomic arrangement in glass. J. Am. Chem. Soc. 1932, 54, 3841-3851. doi: 10.1021/ja01349a006.

[26] Rincon, J.M. Principles of Nucleation and Controlled Crystallization. Wiley-VCH: Weinheim, Germany, 2007.

[27] Rincon, J.M. Principles of Nucleation and Controlled Crystallization. Wiley-VCH: Weinheim, Germany, 2007.

[28] Rawlings, R.D.; Wu, J.P.; Boccaccini, A.R. Glass-ceramics: Their production from wastes-A Review. J. Mater. Sci. 2006, 41, 733-761. doi: 10.1007/s10853-006-6554-3.

[29] Montazerian, M.; Zanotto, E.D. History and trends of bioactive glass-ceramics. J. Biomed. Mater. Res. A 2016, 104, 1231-1249. doi: 10.1002/jbm.a.35639.

[30] Fernandes, H.R.; Gaddam, A.; Rebelo, A.; Brazete, D.; Stan, G.E.; Ferreira, J.M.F. Bioactive glasses and glass-ceramics for healthcare applications in bone regeneration and tissue engineering. Materials (Basel) 2018, 11, 1-54. doi: 10.3390/ma11122530.

[31] Karamanov, A.; Maccarini Schabbach, L.; Karamanova, E.; Andreola, F.; Barbieri, L.; Ranguelov, B.; Avdeev, G.; Lancellotti, I. Sinter-crystallization in air and inert atmospheres of a glass from pre-treated municipal solid waste bottom ashes. J. Non.

[32] Casasola, R.; Rincon, J.M.; Romero, M. Glass-ceramic glazes for ceramic tiles: A review. J. Mater. Sci. 2012, 47, 553-582. doi: 10.1007/s10853-011-5981-y.

[33] Ecobasalto. Available online: https://www.ecobasalto.pt (accessed on 18 July 2020).

[34] Beall, G.H.; Corning, H.L.; Rittler, L. Glass Science and Technology, Vol. 1: Glass-Forming Systems; Academic Press: New York, NY, USA, 1983.

[35] E.D. Zanotto, J.C. Mauro, The glassy state of matter: Its definition and ultimate fate, J. Non. Cryst. Solids 471 (2017) 490–495, http://dx.doi.org/10.1016/j.jnoncrysol.2017.05.019.

[36] Demech India (2019). http://www.demechindia.com (accessed 18.07.20).

[37] Kalenborn (2017). https://www.kalenborn.com/en-us/products/wear-protection-materials/abresist/ (accessed 25.03.20).

[38] Eutit (2010). https://www.eutit.com/products.html (accessed 18.07.20).

[39] J.M. Rincon, Principles of Nucleation and Controlled Crystallization An Introduction, 8th ed., John Wiley & Sons, Inc, 2010.

[40] J. Shackelford, Introduction to Materials Science for Engineers, 8th ed., Pearson Higher Education, Inc, Nova Jersey, 2014.

[41] W.H. Zachariasen, The atomic arrangement in glass, J. Am. Chem. Soc. 54 (1932) 3841–3851, http://dx.doi.org/10.1021/ja01349a006.

[42] H.R. Fernandes, A. Gaddam, A. Rebelo, D. Brazete, G.E. Stan, J.M.F. Ferreira, Bioactive glasses and glass-ceramics for healthcare applications in bone regeneration and tissue engineering, Materials (Basel) 11 (2018) 1–54, http://dx.doi.org/10.3390/ma11122530.

[43] M. Montazerian, E.D. Zanotto, History and trends of bioactive glass-ceramics, J. Biomed. Mater. Res. A 104 (2016) 1231–1249, http://dx.doi.org/10.1002/jbm.a.35639.

[44] M. Romero, J.M. Rincon, R. Casasola, Glass-ceramic glazes for ceramic tiles: A review, J. Mater. Sci. 47 (2012) 553–582, http://dx.doi.org/10.1007/s10853-011-5981-y.

[45] Khater et al., Technical glass-ceramics from granite quarry waste using a fast firing cycle, J. Eur. Ceram. Soc. 41 (2021) 1–10,

https://doi.org/10.1016/j.jeurceramsoc.2020.08.052.

[46] J. Wang, Y. Wang, Y. Zhang, Y. Li, Y. Liu, Y. Zhang, Preparation and characterization of glass-ceramics from coal fly ash and waste glass, J. Mater. Sci. 55 (2020) 11809–11822, https://doi.org/10.1007/s10853-020-04998-5.

[47] A. Kaur, S. Singh, S. Singh, S. Singh, Utilization of waste glass in the synthesis of glass-ceramics: A review, J. Mater. Sci. 55 (2020) 11823–11844, https://doi.org/10.1007/s10853-020-04999-4.

[48] S. Karamanov, M. Karamanova, V. Kancheva, V. Petrov, Glass-ceramics from waste materials: A review, J. Mater. Sci. 55 (2020) 11845–11863, https://doi.org/10.1007/s10853-020-05000-1.

[49] S. Karamanov, M. Karamanova, V. Kancheva, V. Petrov, Glass-ceramics from waste materials: A review, J. Mater. Sci. 55 (2020) 11845–11863, https://doi.org/10.1007/s10853-020-05000-1.

[50] M. Romero, J.M. Rincon, R. Casasola, Glass-ceramic glazes for ceramic tiles: A review, J. Mater. Sci. 47 (2012) 553

[51] Demech India (2019). http://www.demechindia.com (accessed 18.07.20).

[52] Kalenborn (2017). https://www.kalenborn.com/en-us/products/wear-protection-materials/abresist/ (accessed 25.03.20).

[53] Eutit (2010). https://www.eutit.com/products.html (accessed 18.07.20).

[54] Khater et al., Technical glass-ceramics from granite quarry waste using a fast firing cycle, J. Eur. Ceram. Soc. 41 (2021) 1–10, https://doi.org/10.1016/j.jeurceramsoc.2020.08.052.

[55] J.M. Rincon, Principles of Nucleation and Controlled Crystallization An Introduction, 8th ed., John Wiley & Sons, Inc, 2010.

[56] J. Shackelford, Introduction to Materials Science for Engineers, 8th ed., Pearson Higher Education, Inc, Nova Jersey, 2014.

[57] W.H. Zachariasen, The atomic arrangement in glass, J. Am. Chem. Soc. 54 (1932) 3841–3851, http://dx.doi.org/10.1021/ja01349a006.

[58] M. Romero, J.M. Rincon, R. Casasola, Glass-ceramic glazes for ceramic tiles: A review, J. Mater. Sci. 47 (2012) 553–582, http://dx.doi.org/10.1007/s10853-011-5981-y.

[59] Khater et al., Technical glass-ceramics from granite quarry waste using a fast firing cycle, J. Eur. Ceram. Soc. 41 (2021) 1–10, https://doi.org/10.1016/j.jeurceramsoc.2020.08.052.

[60] Demech India (2019). http://www.demechindia.com (accessed 18.07.20).

[61] Kalenborn (2017). https://www.kalenborn.com/en-us/products/wear-protection-materials/abresist/ (accessed 25.03.20).

[62] Eutit (2010). https://www.eutit.com/products.html (accessed 18.07.20).

[63] H.R. Fernandes, A. Gaddam, A. Rebelo, D. Brazete, G.E. Stan, J.M.F. Ferreira, Bioactive glasses and glass-ceramics for healthcare applications in bone regeneration and tissue engineering, Materials (Basel) 11 (2018) 1–54, http://dx.doi.org/10.3390/ma11122530.

[64] M. Montazerian, E.D. Zanotto, History and trends of bioactive glass-ceramics, J. Biomed. Mater. Res. A

104 (2016) 1231–1249, http://dx.doi.org/10.1002/jbm.a.35639.

[65] J.M. Rincon, Principles of Nucleation and Controlled Crystallization An Introduction, 8th ed., John Wiley & Sons, Inc, 2010.

[66] J. Shackelford, Introduction to Materials Science for Engineers, 8th ed., Pearson Higher Education, Inc, Nova Jersey, 2014.

[67] Khater et al., Technical glass-ceramics from granite quarry waste using a fast firing cycle, J. Eur. Ceram. Soc. 41 (2021) 1–10, https://doi.org/10.1016/j.jeurceramsoc.2020.08.052.

[68] J.M. Rincon, Principles of Nucleation and Controlled Crystallization An Introduction, 8th ed., John Wiley & Sons, Inc, 2010.

[69] J. Shackelford, Introduction to Materials Science for Engineers, 8th ed., Pearson Higher Education, Inc, Nova Jersey, 2014.

[70] R. Casasola, J.M. Rincón, M. Romero, Glass-ceramic glazes for ceramic tiles: A review, J. Mater. Sci. 47 (2012) 553–582, http://dx.doi.org/10.1007/s10853-011-5981-y.

[71] Y. Hendro et al., “The local mineral potential from East Lampung - Indonesia: the use of basalt rock as a stone meal for cassava plant,” J. Degrad. Min. Lands Manag., vol. 7, pp. 1977–1985, Oct. 2019, doi: 10.15243/jdmlm.2019.071.1977.

[72] I. Sukmana, Y. Hendronursito, S. Savetlana, K. Isnugroho, M. Amin, and D. C. Birawidha, “Characterization and Potential Production of Glass-Ceramics Biomaterial from Basalt Rock of Local Lampung Province,” Int. J. Technol., vol. 13, no. 4, pp. 870–879, 2022, doi: 10.14716/ijtech.v13i4.4958.