Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

A New Environmental-Friendly Approach to Preparing Glass-Ceramics from Desert Sand

Qi Hu[1], Wenbin Wang[1,*], Ao Yu[2], Wenli Luo[3], Junfei Gu[1], Xiaoqing Yi[1], Linhui Zhou[1], Zhiming Shi[1]

[1] School of Materials Science and Engineering, Inner Mongolia University of Technology, Hohhot 010051, China;
[2] Nanoscience Technology Center, University of Central Florida, Orlando, FL 32816, USA;
[3] School of Aeronautics, Inner Mongolia University of Technology, Hohhot 010051, China.

* Correspondence: wenbinwang@imut.edu.cn

Abstract. The word's mineral resources are sharply decreasing, and the process of desertification is severe. The use of desert sand as a substitute for natural materials is of great significance for reducing the consumption of mineral resources and protecting the environment. Desert sand contains a large amount of SiO_2. Using desert sand to replace pure oxides not only saves costs and natural minerals, but also enhances the comprehensive utilization of desert resources, which meets the requirements of sustainable development. This paper reviews the research status of the preparation of glass-ceramics with desert sand as the main raw material, including the resource status of desert sand, the preparation process and application of glass-ceramics. The advantages and challenges of preparing glass-ceramics from desert sand were studied. Finally, the future development direction of glass-ceramics prepared from desert sand was prospected.

Keywords: Desert Sand; Glass-Ceramics; Preparation Process; Comprehensive Utilization of Resources; Environmental Protection

1. Introduction

1.1. Status of Desert Sand Resources

Arid and semi-arid areas account for more than 33% of the Earth's land area, and deserts account for about 12% of the Earth's land area [1]. Figure 1 shows a map of the distribution of the world's deserts, with desert-covered areas in orange (Central Asian Desert (CA), East Asian Desert (EA), South-West Asian Desert (SWA), North American (NAM), South American Desert (SAM), North African Desert (NAF), South African Desert (SAF) and Australian Desert (AU)). The Sahara Desert with a total area of about 9.4 million km^2, located in Africa and spanning a number of countries in North Africa, is the world's largest desert. The other deserts include the largest deserts of Rupa Hari located in South-West Asia, Rupshali in Southwest Asia, Great Victoria in Australia, and Taklamakan in East Asia. Desert sand is abundant globally, but historically has not been widely used in construction due to its smooth surface texture [2]. However, desert sand contains minerals such as quartz, mica, pyroxene, hornblende, apatite, etc. The use of desert sand in construction materials not only prevents environmental degradation caused

Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

by excessive river sand mining, but also reduces carbon emissions and energy consumption, which is in line with the requirements of sustainable development [3].

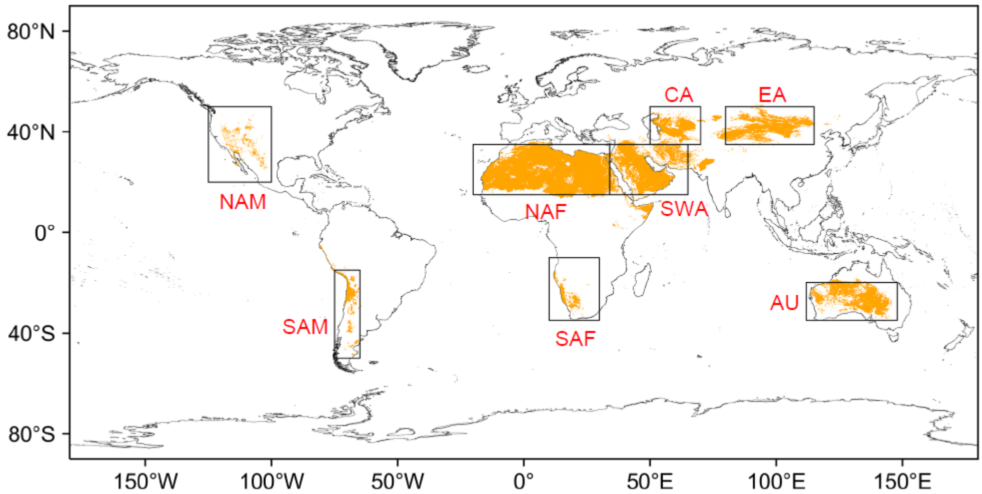

Figure 1. Global Distribution of Deserts.

Severe desertification and the deepening contradiction between the increased use of inorganic products and the decrease in mineral resources provide the necessity to choose desert sand as a raw material for glass-ceramics, the preparation of which using desert sand links materials, manufacturing, mineral and earth resources, ecological environment, and social and economic and sustainable development [4].

Desert sand contains a large amount of SiO_2, and a small amount of Fe, Na, K, Ca, Ti and other elements can act as co-solvents and nucleating agents, which can be used to prepare glass-ceramics instead of silicate minerals [5]. For example, Wang Zidong [6] et al. successfully prepared dense cordierite glass-ceramics by using desert sand instead of SiO_2 without any addition of nucleating agents and co-solvents and investigated the effect of desert sand on crystallization, densification and properties. The synthesis of glass-ceramics using desert sand instead of high-purity raw materials and natural mineral raw materials reduces the consumption of natural minerals, which not only saves the production cost, but also improves the comprehensive utilization of desert resources, which is in line with the requirements of sustainable development.

1.2. Glass-Ceramics

Glass-ceramics s is a new, high-performance material containing many tiny crystals and glass phases. It is a composite material consisting of microscopic crystals and amorphous phases characterized by an amorphous body containing ordered crystals [7]. Glass-ceramics has excellent properties such as high temperature resistance, thermal shock resistance, adjustable thermal expansion, etc. and can be manufactured into a variety of components to meet structural and functional needs, which not only has high economic benefits, but also has the potential to replace traditional building materials.

There are two types of glass-ceramics based on composition classification, oxides and non-oxides. Oxide-based glass-ceramics can be divided into silicate, borate and phosphate glass-ceramics, and non-oxide-based glass-ceramics can be chalcogenides, halides and metal types, depending on their composition [8]. Among them, CaO-MgO-Al_2O_3-SiO_2 glass-ceramic is one of the most promising glass-ceramic systems in oxide-based glass-ceramics. Different crystal phases can be formed at different temperatures, such as diopside ($CaMgSi_2O_6$), anorthite ($CaAl_2Si_2O_8$), cordierite ($Mg_2Al_4Si_5O_{18}$), etc. Therefore, CMAS glass-ceramics have the characteristics of high hardness and wear resistance [9]. However, the glass composition, the type of dopant and different heat treatment processes all control the crystal phase type and grain size of glass-ceramics to a certain extent, thus affecting the microstructure and properties [10].

Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

Diopside glass-ceramics belong to the CaO-MgO-Al_2O_3-SiO_2 (CMAS) system. Like other glass-ceramics, the crystals in diopside glass-ceramics are formed by the controllable crystallization of glass. Due to the low price, diopside glass-ceramics have received extensive attention in recent years [11]. Diopside glass-ceramics have interlaced structure under the microscope. This kind of glass-ceramics has the advantages of high strength, good wear resistance and chemical corrosion resistance. Domestic and foreign researchers agree that the use of solid waste as a raw material to prepare glass-ceramics is an effective way of resource utilization [12]. The preparation of diopside glass-ceramics with desert sand as the main raw material and adding appropriate flux and nucleating agent is an important direction of glass-ceramics research.

2. Research Status of Preparation of Glass-Ceramics from Desert Sand

2.1. The Existing Technical Route of Preparing Glass-Ceramics from Desert Sand

The main component of desert sand is SiO_2, which can reach 90%-97.63%, but contains a small amount of impurities (e.g., iron oxide, alumina, etc.) that need to be pre-treated by screening, magnetic separation, and other techniques in order to improve the purity. Studies have shown that pretreated desert sand can be melted at high temperatures (1500-1600°C), combined with crystallization heat treatment (e.g., adding nucleating agents or controlling the cooling rate) to form a multiphase composite structure dominated by α-quartz, β-spinel and glassy phases. Typically, a team from Inner Mongolia University of Technology [6,13] successfully prepared quartz and cordierite glass-ceramics by adding feldspar, kaolin, and other auxiliary materials from Kubuqi desert sand as raw materials. In which, the bending strength can reach more than 80 MPa, and the Vickers hardness and bending strength of the quartz glass-ceramics increase with an increase of the sintering temperature and the holding time, as shown in Figure 2.

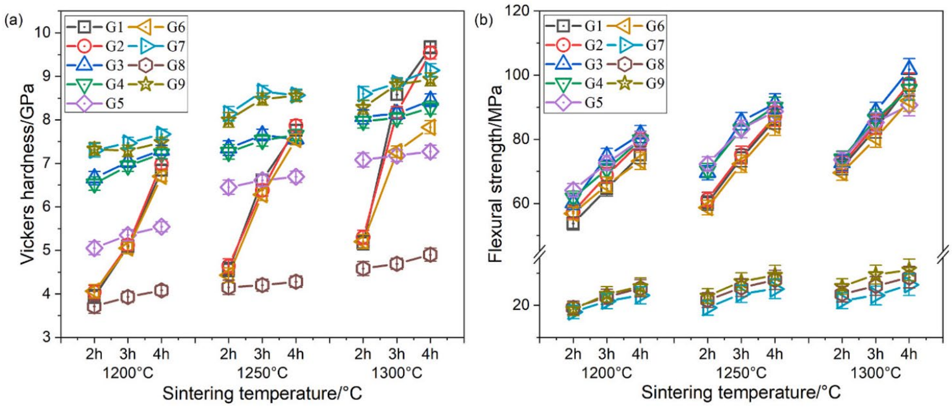

Figure 2. The mechanical properties of quartz glass ceramics prepared at different sintering temperature and holding time: (a) Vickers hardness, (b) mechanical strength.

It has been found that [14] CMAS glass-ceramics prepared from desert sand has good physical, thermal and mechanical properties with potential applications in building insulation and thermal insulation. Figure 3 shows the Vickers indentations on CMAS glass-ceramics using 1.96, 2.9, 4.9 and 9.8 N indentation loads as observed under optical microscope using Vickers microhardness measurements in this study. And it was found that the Vickers microhardness value of desert sand glass is the same as that of other silicate glass by calculation. It provides a direction for the utilization of desert sand instead of natural materials to improve the comprehensive utilization of desert sand.

Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

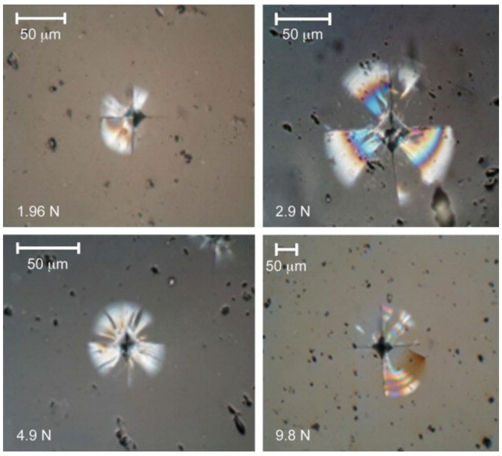

Figure 3. Indentations under different loads.

Xu et al. [15] investigated the effect of different heat treatment processes on the crystallization of glass-ceramics, a part of the samples were held at their glass transition temperature for a period of time for structural adjustment, and then heated to the glass optimal crystallization temperature for crystallization heat treatment; a part of the samples were heat-treated by the traditional two-step method; and the other part of the samples were heat-treated by a one-step method, which allowed the glass to be held at the crystallization temperature before being heated to 1000°C for sub-crystallization, and the crystallinity of the glass-ceramics can generally be improved by increasing the glass crystallization holding time and elevating the glass crystallization temperature. A proper heating method will cause phase transition, compounding of crystal structure, and coarsening and growth of microcrystals in oxide materials, helping us to study the crystal structure in detail [16]. Microcrystalline glasses prepared using incremental glass transition temperature holding time, crystallization temperature and secondary crystallization yielded higher crystallinity compared to those synthesized through the conventional two-step nucleation crystallization method.

2.2. Application Status of Glass-Ceramics

Glass-ceramics have excellent properties such as high mechanical strength, adjustable thermal expansion, chemical corrosion resistance, and low dielectric loss. In recent years, with the progress of material science and preparation technology, its application fields have been expanding, covering key fields such as construction [17], electronic semiconductors, medical treatment, and new energy [18]. Glass-ceramics have become one of the core materials to promote industrial upgrading. In the future, it is necessary to focus on solving the problem of cost and performance balance in large-scale production, and strengthen interdisciplinary cooperation to tap its potential value.

3. Advantages and Challenges of Desert sand Preparation of Glass-Ceramics

3.1. Advantages of Desert Sand Preparation of Glass-Ceramics

Deserts occupy a huge area of land in the world and pose great harm to farmland, transportation, infrastructure, ecological environment and human health. Although desertification has been controlled by planting desert plants and protecting the existing vegetation, the problem of desertification has not been solved well [19]. Therefore, the use of desert sand to manufacture industrial products helps to slow down the process of desertification, reduce mineral exploitation and land destruction, which is an effective measure to improve the desert ecological environment.

High purity SiO_2 is the basic component of glass-ceramics. The main component of desert sand is high content of SiO_2.Compared with the traditional raw material of glass-ceramics, the purity of silica sand is slightly lower, which can be directly used to prepare silicate materials. In addition, desert sand contains a small amount of calcium oxide, alumina and magnesium oxide, which matches the requirements of auxiliary oxides in traditional glass-ceramic formulations. These elements can be used

Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

as nucleating agents or network modifiers to promote crystal phase precipitation and glass phase stability. The average particle size of desert sand is very small, about a few microns. It can effectively reduce the generation of bubbles and defects in the process of melting or sintering to form a glass matrix. At the same time, the fine particles of desert sand meet the requirements of the sintering process of glass ceramics for the particle size of raw materials. Table 1 shows the advantages of traditional methods using ore or pure quartz sand as raw materials and using desert sand as a source of silicate.

Table 1. Comparison of the two materials.

Raw materials	Characteristics
ore or pure quartz sand	No pretreatment is required; increase the transparency and hardness of the finished product
desert sand	Achieve low-cost green manufacturing of silicate materials; the products prepared by desert sand show comparable or even better performance than those prepared by traditional raw materials. Save more mineral resources

3.2. Challenges in the Preparation of Glass-Ceramics from Desert Sand

Although a large number of studies have made some products in practice, there are still many problems to be solved. In fact, desert sand is small in size, poor in degradation, spherical in shape, and difficult to be closely integrated into the matrix material. The physical and chemical properties of desert sand cannot meet the specifications of some raw materials for manufacturing inorganic materials. The treatment of impurities in desert sand requires additional energy consumption, and large-scale production needs to optimize the screening and magnetic separation process. Due to the excessive impurity elements in desert sand, it may interfere with the crystallization process of glass-ceramics in the process of preparing glass-ceramics. Desert sand is mostly distributed in remote areas, and the cost of transportation to industrial areas is high, which will lead to the high cost of commercialization of glass-ceramics prepared from desert sand.

In addition, studies have shown that desert sand will be transformed into calcium magnesium aluminosilicate (CMAS) glass when it melts, which is sensitive to slow crack growth and indentation damage [20]. CMAS is usually deposited on the surface of the hot section components of the turbine engine to form glass, and its fracture behavior affects the integrity of the environmental barrier coating and the thermal barrier coating. Similar to many silicate glass-ceramics, it exhibits sensitivity to slow crack growth behavior.

4. Conclusion

Desert sand-based glass-ceramics have shown the potential to replace traditional materials in the construction, industrial and energy fields, and their resource richness and environmental friendliness meet the needs of sustainable development. However, further breakthroughs are still needed in terms of technical cost and energy efficiency. In terms of impurity control and crystal phase design, the crystallization behavior and properties of glass-ceramics prepared from desert sand can be optimized by ion doping such as Li^{+} and Mg^{2+}. With process optimization and interdisciplinary cooperation, desert sand glass-ceramics are expected to become an important direction for green material innovation.

Acknowledgments: This work was supported by the First-Class Discipline Scientific Research Special Project, Inner Mongolia University of Technology of China (No. YLXKZX-NGD-002).

Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

Conflict of Interest: The authors declare that there is no conflict of interest regarding the publication of this article.

Reference

[1] Chen Y., Lu H., Wu H., et al. Global desert variation under climatic impact during 1982–2020. Science China Earth Sciences, 2023, 66(5): 1062-1071. https://doi.org/10.1007/s11430-022-1052-1

[2] Gavriletea M.D. Environmental Impacts of Sand Exploitation. Analysis of Sand Market. SUSTAINABILITY, 2017, 9(7): 1118. https://doi.org/10.3390/su9071118

[3] Huynh T-P., Ho L.S., Ho Q.V. Experimental investigation on the performance of concrete incorporating fine dune sand and ground granulated blast-furnace slag. Construction and Building Materials, 2022, 347: 128512. https://doi.org/10.1016/j.conbuildmat.2022.128512

[4] Shi Z.M. Green manufacturing of silicate materials using desert sand as a raw-material resource. Construction and Building Materials, 2022, 338: 127539. https://doi.org/10.1016/j.conbuildmat.2022.127539

[5] Luo H.W., Shi Z.M., Wang H.H., et al. The microstructure, phase transformation and sinterability of desert sand. Materials Today Communications, 2023, 35: 105685. https://doi.org/10.1016/j.mtcomm.2023.105685

[6] Wang Z.D., Liu Z.W., Wang W.B., et al. Effect of desert-sand replacing pure SiO_2 on crystallization, densification and properties of cordierite glass-ceramic. Journal of Materials Research and Technology, 2024, 31: 2202-2216. http://doi.org/10.1016/j.jmrt.2024.07.001

[7] Deubener J., Allix M., Davis M.J., et al. Updated definition of glass-ceramics. Journal of Non-Crystalline Solids, 2018, 501: 3-10. http://doi.org/10.1016/j.jnoncrysol.2018.01.033

[8] Karmakar B. 1 - Introduction to functional glasses and glass-ceramics [M]//KARMAKAR B. Functional Glasses and Glass-Ceramics. Butterworth-Heinemann. 2017: 3-21. https://doi.org/10.1016/B978-0-12-805056-9.00001-5

[9] Xiao H.N., Cheng Y., Yu L.P., et al. A study on the preparation of CMAS glass–ceramics by in situ crystallization. Materials Science and Engineering: A, 2006, 431(1): 191-195. https://doi.org/10.1016/j.msea.2006.05.153

[10] Guo X.ZH., Cai X.B., Song J., et al. Crystallization and microstructure of $CaO–MgO–Al_2O_3–SiO_2$ glass–ceramics containing complex nucleation agents. Journal of Non-Crystalline Solids, 2014, 405: 63-7. https://doi.org/10.1016/j.jnoncrysol.2014.08.048

[11] An Z.Q., Gao Y., Chen J.J. Combined effect of La_2O_3 and Fe_2O_3 on the crystallization behavior and microstructure of $CaO-MgO-Al_2O_3-SiO_2$ glass-ceramics. Ceramics International, 2025, 219 :http://doi.org/10.1016/j.ceramint.2025.02.269

[12] Gao H.T., Liu X.H., Chen J.Q., et al. Preparation of glass-ceramics with low density and high strength using blast furnace slag, glass fiber and water glass. Ceramics International, 2018, 44(6): 6044-6053. https://doi.org/10.1016/j.ceramint.2017.12.228

[13] Wang W.B., Song J.W., Shi Z.M., et al. Crystallization behavior and properties of quartz glass-ceramics synthesized from desert sand. Ceramics International, 2024, 50(1A): 370-383. https://doi.org/10.1016/j.ceramint.2023.10.111

[14] Bansal N.P., Choi S.R. Properties of CMAS glass from desert sand. Ceramics International, 2015, 41(3A): 3901-3909. https://doi.org/10.1016/j.ceramint.2014.11.072

[15] Xu W.C., Shen K.X., Cao Z., et al. Crystallization and thermal stability effects on tailings glass-ceramics by various heat treating processes. Materials Chemistry and Physics, 2021, 263: 124334. https://doi.org/10.1016/j.matchemphys.2021.124334

[16] Zdorovets M.V., Kozlovskiy A.L. Study of phase transformations in $Co/CoCo_2O_4$ nanowires. Journal of Alloys and Compounds, 2020, 815: 152450. https://doi.org/10.1016/j.jallcom.2019.152450

[17] Shi X.p., Liao Q.L., Chen K., et al. Foaming process and thermal insulation properties of foamed glass-ceramics prepared by recycling muti-solid wastes. Construction and Building Materials, 2025, 466: 140270. https://doi.org/10.1016/j.conbuildmat.2025.140270

Doi: https://doi.org/10.63333/eem.v1n23 Vol. 1 No. 2 (2025)

[18] Ibrahim S., Ei-Kheshen A.A., Abdel-baki M., et al. Synthesis and characterization of erbium silica glass and glass-ceramics for potential low-emissivity coating applications. Ceramics International, 2025, 51(1): 458-472. https://doi.org/10.1016/j.ceramint.2024.11.021
[19] Chen C., Park T., Wang X.H., et al. China and India lead in greening of the world through land-use management. Nature Sustainability, 2019, 2(2): 122-129. https://doi.org/10.1038/s41893-019-0220-7
[20] Kedir N., Faucett D.C., Choi S.R, et al. Slow-crack-growth and indentation damage in calcium magnesium aluminosilicate (CMAS) glass from desert sand. Ceramics International, 2018, 44(3): 2676-2682. https://doi.org/10.1016/j.ceramint.2017.10.194