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Atiar R. Molla
Annapurna Kalyandurg
J. M. Parker *Editors*

Advances in Glass and Glass-Ceramics

Proceedings of International Conference on Advances in Glasses and Glass-Ceramics 2022

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Foreword

This volume celebrates the United Nations International Year of Glass 2022.

A dream comes true.

In May 2021, the news keenly anticipated by glass communities everywhere went around the world. **The United Nations endorsed 2022 as the International Year of Glass (IYoG2022)**. The application had taken 18 months to prepare and included a 30-minute video, an electronic brochure and a variety of documents explaining the vital role glassy materials play in helping the world achieve the humanitarian goals encompassed in the UN 2030 declarations.

The responsibility for submitting the application rested largely with the '*International Commission on Glass (ICG)*', with support from '*the Community of Glass Associations*' and '*the International Committee for Museums and Collections of Glass*' (*ICOM-Glass*).

Nineteen countries co-sponsored the formal UN Resolution A/75/L.84, approving the International Year of Glass. More than 2600 institutions, companies, artists and individuals from 96 countries all over the world supported this common dream with a commitment to developing activities on education, science, industry and art all over the planet.

The IYOG2022 celebrated its first international event in Geneva with an Opening Ceremony during 9–11 February in the Human Rights Auditorium at the UN Palace of Nations. An array of internationally recognised speakers explained the role that glass can take in relation to the UN 2030 goals. The live audience was restricted to 140 participants by the devastating COVID-19 pandemic, but more than 7000 attendants followed the event online—the highest attendance at one glass event in history, and the largest audience for a United Nations event so far.

Many countries created their own Opening Events with participants from Research Centres, Universities, Industry and Education plus a broad range of glass artists and museum curators.

The book, ***Welcome to the Glass Age/La Edad del Vidrio,*** focused on UN 2030 goals was published in English and Spanish and distributed worldwide by CSIC. Both editions are sold out.

The 26th ICG Congress was organized in Berlin in July 2022, celebrating the DGG's centenary. Many other national and international congresses and conferences were developed under the umbrella of IYOG2022, for example the US Glass Day at Washington DC in April, an Iberoamerican Congress Women in Glass. Artists and Scientists, in Madrid in May, an International Festival of Glass, Stourbridge, UK, in August, or the Italian Glass Weeks at Milano-Venice in September 2022.

Several Trade Fairs focused on IYOG2022 and the role of Glass in Society, particularly Vitrum 2021, GLASSMAN, Monterrey, 11–12 May, MIR STEKLA, Moscow, 6–9 June, GLASSTECH, Düsseldorf, 20–23 September 2022; and Glasspex/Glasspro in Mumbai in 2023.

The Closing Ceremony in Tokyo during 8th–9th December summarized the effort of so many countries, associations, researchers, companies and artists who had worked together, to show the potential of glass to construct a brilliant and sustainable future.

IYOG2022 concluded with a visit to the General Assembly of the United Nations in New York on 14 December 2022. Under Natalie Tyler's sculpture '*Wildfire*', representing the effect of climate change on the environment, a huge gathering reported on what the glass community had achieved and to confirm our commitment to extend the use of glass to ensure a more sustainable and fair planet and societies.

Thousands of events were organized locally with the support of the central organization, sustained by a Council of 75 members and a website (https://iyog2022.org/) that offered access to the IYOG logo and a network of contacts to share ideas and materials such as posters, display boards, articles, comics and YouTube clips.

The help of sponsors was crucial to organize and finance the Opening Ceremony in Geneva. We received close to half a million euros from an important range of companies, suppliers and associations. Half of this was invested in seed fund projects, selected from calls published in April and July 2022. Eighty six projects from 26 countries were financed, focused mainly on educational activities and art.

The most important journals related to glass published special issues (JNCS, IJAGS, Heritage, La Revista, JSST, Optical Materials) and glass magazines (Glass International, Glass Worldwide, Physic World, Vidrio y Perfil, etc.) kept a wide public continuously informed of events and activities.

Particularly important were the books edited under the umbrella of IYOG. The first was 'Welcome to the Glass Age', but others followed such as the *Historia cultural do vidro na arquitetura*, published in Brazil; the *National Day of Glass* in the USA; and *Les secrets du verre* in France.

India was very proactive in celebrating IYOG2022: for example, they conducted monthly seminars on glass given by eminent speakers from across the globe and arranged laboratory visits by local school children to increase awareness among younger minds of the vital roles that glass plays in sustainable society. An International Conference on "Advances in Glass and Glass-Ceramics (ICAGGC-2022)" was organized by the CSIR-Central Glass and Ceramic Research Institute (CSIR-CGCRI), Kolkata, India, in hybrid mode. The ICAGGC-2022 was a truly remarkable event with the lectures comprising two keynote talks, seven plenary lectures and 11 invited talks by eminent speakers from all over the world. The conference was enriched by 28 oral and 48 poster presentations. All the presentations were of a truly international standard, and the delegates benefitted immensely from these deliberations. The organizers of the ICAGGC-2022 in collaboration with Springer Nature, Singapore, decided to publish selected papers from the conference as a Proceedings Volume to disseminate knowledge on glass. I congratulate CSIR-CGCRI and Springer Nature for this noble initiative and for their painstaking efforts to bring out this very important book. The book contains 14 chapters comprising various advanced research topics selected for publication after peer review.

I hope that all the readers—researchers, students, technicians—will be inspired by this book to grasp the opportunity to understand and promote glass. This book, as every activity developed within the framework of IYOG2022, has as its main goal to contribute to the building of more sustainable and fairer societies, following the roadmap to a better planet in the Age of Glass.

Alicia Durán
Research Professor CSIC
Chair of the UN International Year
of Glass 2022
Instituto de Cerámica y Vidrio
Madrid, Spain

Preface

It is with great pleasure and pride that we present to you the proceedings of the International Conference on Advances in Glass and Glass-ceramics (ICAGGC-2022), captured in this volume titled *Advances in Glass and Glass-Ceramics*. This collection embodies the culmination of extensive research, profound insights, and collaborative efforts dedicated to the exploration and innovation within the realm of glass science and technology.

The ICAGGC-2022, organized by the CSIR-Central Glass and Ceramic Research Institute, Kolkata, India, stands as a testament to the global recognition of the pivotal role that glass plays in our contemporary world. Convened in the hybrid mode from 23rd to 25th August 2022, this conference was a notable initiative under the United Nations International Year of Glass 2022, in collaboration with esteemed partners including the All India Glass Manufacturers' Federation (AIGMF), the Indian Ceramic Society (ICS) Kolkata Chapter, and the Glazing Society of India (GSI).

The United Nations declaration of 2022 as the International Year of Glass heralded a momentous occasion, celebrating the multifaceted significance of glass in society. This recognition prompted a concerted effort to foster awareness and appreciation for the diverse applications and contributions of glass across various domains. Through collaborative endeavors and regional organizing committees, the year sought to highlight the intrinsic value of glass as a material that transcends boundaries and enriches lives.

In today's landscape, glass has emerged not only as a symbol of architectural elegance but also as a cornerstone of technological advancement. From state-of-the-art skyscrapers adorned with versatile and self-cleaning glass facades to the ubiquitous presence of shatter-proof touch screens in our daily electronic devices, the adaptability and utility of glass are truly unparalleled. Moreover, the advent of high-purity silica glass has revolutionized optical communication, paving the way for unprecedented advancements in telecommunication.

The ICAGGC-2022 served as a dynamic platform for scholars, researchers, industry experts, and enthusiasts to converge, exchange ideas, and push the boundaries of glass science and technology further. With over a hundred papers presented, including keynote lectures, plenary sessions, invited talks, and poster presentations, the conference encapsulated a rich tapestry of knowledge and innovation.

This compendium, comprising 14 chapters, encapsulates the diverse spectrum of topics explored during the conference. We believe that the insights and findings shared within these pages will not only broaden the understanding of glass science but also catalyze future advancements in the field. Our sincere hope is that this volume will serve as a valuable resource for researchers, academics, and practitioners alike, fostering continued exploration and innovation in the science and technology of glasses and glass-ceramics.

We extend our heartfelt gratitude to all the contributors, organizers, and supporters who made ICAGGC-2022 a resounding success. Special thanks are due to Prof. Alicia Duran for her invaluable contributions as the chairperson of IYoG 2022 and for her inspiring foreword to this book. We also acknowledge the unwavering support and guidance provided by Dr. (Mrs.) Suman Kumari Mishra, Director of CSIR-CGCRI, Kolkata, and Mr. Sitendu Mandal, Chief Scientist and Head of the Specialty Glass Division. We express our gratitude for the invaluable contributions made by the scientists and staff of the Specialty Glass Division at CSIR-CGCRI, Kolkata, for their dedication to organizing this conference and producing this book volume.

Last but not the least, we express our profound appreciation to the General Assembly of the United Nations for their visionary resolution in declaring 2022 as the International Year of Glass, recognizing the profound impact of glass on society and the strides made in advancing its science and technology.

May this volume serve as a beacon, illuminating the path toward a future where glass continues to inspire, innovate, and enrich lives across the globe.

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About the Editors

Dr. Atiar R. Molla currently serves as a Senior Principal Scientist at CSIR-Central Glass and Ceramic Research Institute, Kolkata, India and holds a professorship at the Academy of Scientific and Innovative Research (AcSIR) within the Engineering Science Division. He earned his B.Tech. in Ceramic Technology from the Government College of Engineering and Ceramic Technology, Kolkata, his M.Tech. from IIT Kanpur, and his Ph.D. from Jadavpur University, Kolkata. With over 20 years of research experience in specialty glasses and glass-ceramics, Dr. Molla has also contributed as a Visiting Scientist at the Federal University of Sao Carlos, Brazil. His research has taken him to various countries, including Brazil, USA, Canada, Germany, Singapore, and Turkey. Dr. Molla has authored more than 50 research papers in prestigious international journals, contributed to three book chapters, and holds seven granted patents. He served as the editor of the book *Glasses and Glass-Ceramics—Advanced Processing and Applications*, published by Springer Nature in 2022. Currently, he holds the position of Editor in Chief for the *Journal of Condensed Matter* and serves as Chief Editor for the forthcoming book *Advances in Glass and Glass-Ceramics*, to be published by Springer Nature. He is actively involved with the International Commission on Glass (ICG), serving as a technical committee (TC-23) member on glass education and as Organizing Secretary for the International Congress on Glass 2025, scheduled to take place in India. His current research focuses on transparent ferroelectric/anti-ferroelectric glass-ceramics for multifunctional applications and transparent nanocrystalline ultra-high strength glass-ceramics for display and armor applications.

Dr. Annapurna Kalyandurg is presently working as Chief Scientist at CSIR-Central Glass and Ceramic Research Institute and also serving as Professor at Academy of Scientific and Innovative Research (AcSIR), an Institute of National Importance. She obtained her Ph.D. in 1993 followed by postdoctoral research at Sri Venkateswara University, India. She joined CSIR-Central Glass and Ceramic Research Institute, India, in 1996, and since then, she is actively involved in the research and development of specialty glasses like Nd-doped phosphate laser glass for high power laser systems, infrared absorbing and infrared transmitting filter glasses, non-oxide chalcogenide glasses for thermal imaging applications, space grade optical glasses, including their process technology. Her basic research includes structure and property studies of rare earth/transition metal-doped glasses and transparent glass ceramics for photonic and energy applications. She has around 140+ publications in international and national journals of repute and one Indian and six international patents to her credit. She has served as Lab Coordinator for the Academy of Scientific and Innovative Research (AcSIR) at CSIR-CGCRI. For notable contributions in field of materials science and technology, she has been conferred with the R. L. Thakur Award for Young Scientists 1998.

Prof. J. M. Parker is Emeritus Professor of Glass Science and Engineering, Department of Materials Science and Engineering, The University of Sheffield, Western Bank, Sheffield. Professor John Parker moved to Sheffield from the University of Cambridge in 1971, having completed a first-class M.A. in Natural Sciences, a Ph.D. and a post-doctoral NERC fellowship studying aluminosilicates with incommensurate structures. At Sheffield, he has developed interests in both the optical/structural properties of glasses and the technology of bulk glass making. He is actively involved in the International Commission on Glass and is past-president of both the Society of Glass Technology and the European Society of Glass Science and Technology. His research interests are in glass structural analysis, particularly using information derived by optical spectroscopy, and the processes involved in glass crystallisation. He has worked closely with industry, including organisations such as British Telecom, Pilkingtons, Johnson Matthey, and Rockware Glass. I have also interacted with the Physics Departments at Sheffield, Brunel and Paisley, and with the Rutherford Appleton Laboratories. He has published several books, chapters and research papers.

Assessment of SiO_2-B_2O_3-Na_2O-TiO_2-Fe_2O_3 Glass System for the Vitrification of High-Level Acidic Radioactive Liquid Waste

J. Selvakumar, Sourav Maity, G. Suneel, S. Srinivasan, N. R. Jawahar, and J. K. Gayen

1 Introduction

The heavy metal lean acidic solution in the first stage of the Plutonium Uranium Extraction (PUREX) process in spent nuclear fuel reprocessing is known as High-level Liquid Waste (HLW). Radiotoxicity relevant to the HLW is paramount compared to the other liquid streams of the reprocessing plants. With the high levels of radioactivity >3.7×10^{10} Bq (>1 Ci/L), the number of radionuclides (more than 350 nuclides with different half-life and concentrations), and generation of decay heat, HLW demands isolation from the biosphere for many thousands of years before the radiotoxicity level falls to an inconsequential level [1].

Vitrification is the prime conditioning methodology used worldwide to immobilize the HLW of reprocessing plants [2–4]. Alkali-borosilicate or phosphate-based vitrification offers volume reduction, destruction of organic, and immobilization of radioactive elements. Further, it provides advantages in storage, transportation, and disposal applications [5, 6]. Due to its good solvent nature, reasonably low process temperature, tolerance of variation in waste composition, and reasonably better chemical and radiation durability, borosilicate glasses have become the material for immobilization of HLW through vitrification. The short- and medium-range order in borosilicate glasses offers flexibility for bonding waste, which is constituted differently than in crystalline materials. It is now widely accepted that the performance of a borosilicate waste form with <30% waste oxide loading will meet all the current safety and environmental criteria [7, 8].

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Since HLW composition varies from nation to nation due to the burn-up, cooling time, and process chemistry, freezing base glass's composition for vitrification is challenging. Also, the glass composition is designed based on waste loading, homogeneity, redox state, SiO_2/Na_2O mole ratio, and chemical durability of vitrified waste products. Hence, the present paper details the assessment of the Simulated Vitrified Waste Product (SVWP) prepared with a tailor-made composition of base glass developed and assessed for HLW vitrification and product quality.

2 Materials and Methods

Laboratory-grade nitrate salts of various metals were purchased from CDH Fine Chemicals, India, and SRL Chemicals, India, and used as received. Indigenously developed base glass in the form of glass beads (frit) with specific composition (wt.%) SiO_2 (48.0), B_2O_3 (26.5), Na_2O (11.5), TiO_2 (9.5), Fe_2O_3 (4.5), and SiO_2/Na_2O (4.2) [9] was used as a durable host. Table 1 describes the composition of waste and base glass used to prepare 100 g of SVWPs.

The elemental composition of HLW has been determined using inductively coupled plasma optical emission spectroscopy (ICP-OES). Table 1 summarizes the composition of base glass and a few metal salts/oxides, which are significant contributors to HLW composition. Based on the elemental composition, weighed quantities of the chemicals and pre-formed glass frit were mixed and charged into a sillimanite crucible to prepare the simulated vitrified waste product. The furnace's temperature (mostly 1100 °C) was gradually increased at the heating rate of 5 °C/min. After ensuring the desired pouring temperature and visual homogeneity, the molten mass was kept at the pouring temperature for about 5 h to eliminate the trapped gases and dissolve the crystalline phases, if any. Further, the molten glass was poured into a cold SS mold and allowed to cool to room temperature.

Table 1 Chemical constituents of 100 g of SVWPs (values given are in g)

S. no	Chemicals	VWP-S1			VWP-S2			VWP-S3		
		WO (%)								
		24	26	28	24	26	28	24	26	28
		Weight (g)								
01	SiO_2	36.5	35.5	34.5	36.5	35.5	34.5	36.5	35.5	34.5
02	B_2O_3	19.9	19.5	18.9	19.9	19.5	18.9	19.9	19.5	18.9
03	Na_2O	8.9	8.7	8.4	8.9	8.7	8.4	8.9	8.7	8.4
04	TiO_2	7.2	7.0	6.8	7.2	7.0	6.8	7.2	7.0	6.8
05	Fe_2O_3	3.4	3.3	3.2	3.4	3.3	3.2	3.4	3.3	3.2
06	$Fe(NO_3)_3 \cdot 9H_2O$	6.6	7.2	7.7	6.2	6.7	7.2	3.5	3.8	4.1
07	$NaNO_3$	31.2	33.8	36.4	29.0	31.4	33.9	17.6	19.1	20.6
08	U_3O_8	7.6	7.8	8.4	4.6	5.1	5.5	6.4	6.9	7.4
09	Nd_2O_3	2.5	2.6	2.7	1.6	1.7	1.8	1.0	1.1	1.2

The refined glass sample was used for its characteristics, such as density, homogeneity, glass transition temperature, and chemical durability. Phase analysis of the prepared SVWPs samples was carried out using XRD with CuK_{α} source. A polarized optical microscope was used to investigate the glass matrix's crystalline inclusions, bubbles, and pores. The TG–DTA-DSC (Netzsch STA 449 F5 Jupiter) scan for the prepared products was carried out, and the DTA/DSC head area contains an equivalent sample and reference compartments adjacent. The reference compartment contains an empty Pt–Rh pan and covers equivalent to those used to encapsulate a test sample. The sample compartment is where an encapsulated sample of about 10–15 mg has been placed for testing. The sample is heated at a controlled rate per ASTM (D3418 [10]) methodology, producing a plot of heat flow versus temperature. The resulting thermal scan was then analyzed.

The Product Consistency Test (PCT) methods A and B (ASTM C1285-21 [11]) were applied to study the form of glass waste by measuring the concentrations of Na-ion released into a test solution under carefully controlled conditions. Test method A is a 7-day chemical durability test of powder (63–150 μm) performed at 90 ºC of the leachate in DM water under static conditions using a Teflon-lined stainless-steel vessel. Parameters used in Test Method B are (a) duration (28 days), (b) test temperature (boiling temp. of water), leachate volume (80 mL), particle size (300–850 μm), and system (open).

3 Results and Discussion

As mentioned above, HLW is conditioned by dissolution at the atomic scale in highly durable glassy matrices. The glassy system plays the solvent role for almost all the elements—radioactive/inactive in the waste. Modifiers create non-bridging oxygen (NBO) in the formers when they interact at moderate temperatures. The NBOs carried a negative charge and bonded (ionic) to cations such as Cs^{+}, Sr^{2+}, and others. The structural representation of the SVWP is shown in Fig. 1; among the HLW composition, lanthanides/actinides (Nd shown as an example) may enter into the depolymerized region, and alkaline/alkaline-earth elements (Cs and Sr shown as an example) may enter into both DR and polymerized (PR) region of the glass structure [12].

Based on the experience and requirements to immobilize HLW generated during the recovery of heavy metals from spent nuclear fuel, a five-component base glass studied was formulated with the desired composition of (wt.%) SiO_2 (48.0), B_2O_3 (26.5), Na_2O (11.5), TiO_2 (9.5), and Fe_2O_3 (4.5) and developed indigenously as glass frit. Though various metal oxides are proven as a potential network former, intermediate, and modifier, SiO_2-B_2O_3-Na_2O-TiO_2-Fe_2O_3 system with the desired composition has been selected as a promising candidate to immobilize HLW by considering the following: (i) operation and pouring temperature (800–1000 °C), (ii) T_g (500–550 °C), and (iii) radionuclide volatility. The role of the oxides in the SiO_2-B_2O_3-Na_2O-TiO_2-Fe_2O_3 system is (i) network former: SiO_2-B_2O_3; (ii) network

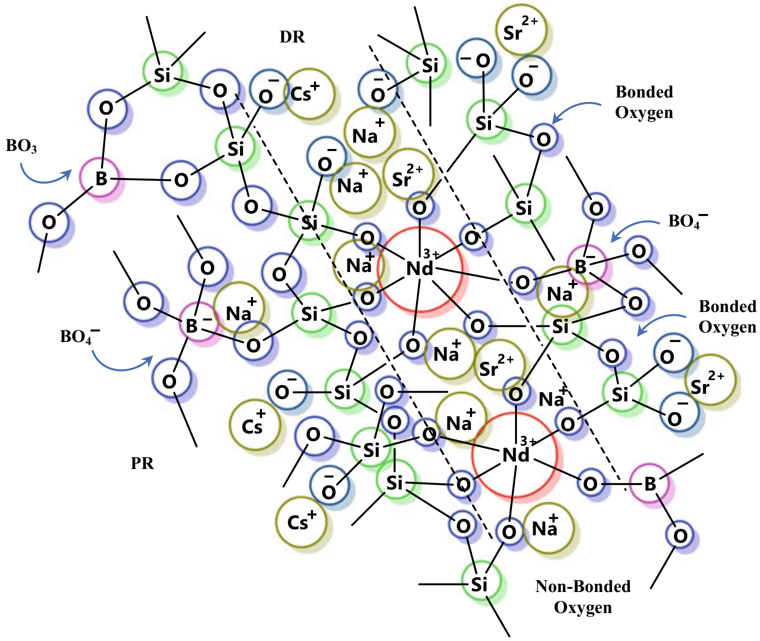


Fig. 1 Schematic representation of the structure of a borosilicate glass containing sodium, strontium, and neodymium (neodymium is the most abundant lanthanide in HLW wastes and a suitable trivalent MA surrogate) [12]; DR—depolymerized; PR—polymerized

modifier: Na_2O; (iii) intermediates: TiO_2-Fe_2O_3. In particular, TiO_2 and Fe_2O_3 are responsible for the depreciation of Cs volatility and electrical conductivity of the melt [13, 14].

The typical procedure followed to prepare glass frit used in the present study is (a) raw chemical processing, (ii) batch preparation, (iii) melting of chemicals and pouring of molten glass, (iv) grinding to powder, (v) frit preparation with the liquid binder, (vi) sieving and modulation, (vii) secondary heat treatment, and (viii) assessment. The assessment includes (i) evaluation of properties of the base glass and (ii) laboratory-scale vitrification of simulated HLW for use on an industrial scale. Based on earlier studies, the preparation of SVWP was limited to the waste oxide (WO) loading from 24 to 28% [9].

The observation during the preparation of VWP-S1 is shown in Fig. 2 (*a*–*i*). The same procedure was followed for preparing VWP-S2 and S3 (Table 1). Experimental observations indicate the pouring temperature of the base glass to be 975 °C compared to the pouring temperature of 950–970 °C of the waste glasses (Table 2). A decrease in pouring temperature, 950 °C, of waste glass can be attributed to the higher sodium content of the waste, which induces discontinuity in the three-dimensional network by forming non-bridging oxygen atoms. The above results indicate that glasses (VWP-S1 and S2) prepared from all waste oxide (WO) loading (24–28%) in these studies are pourable at 950 °C, which is within the range of plant operating temperature.

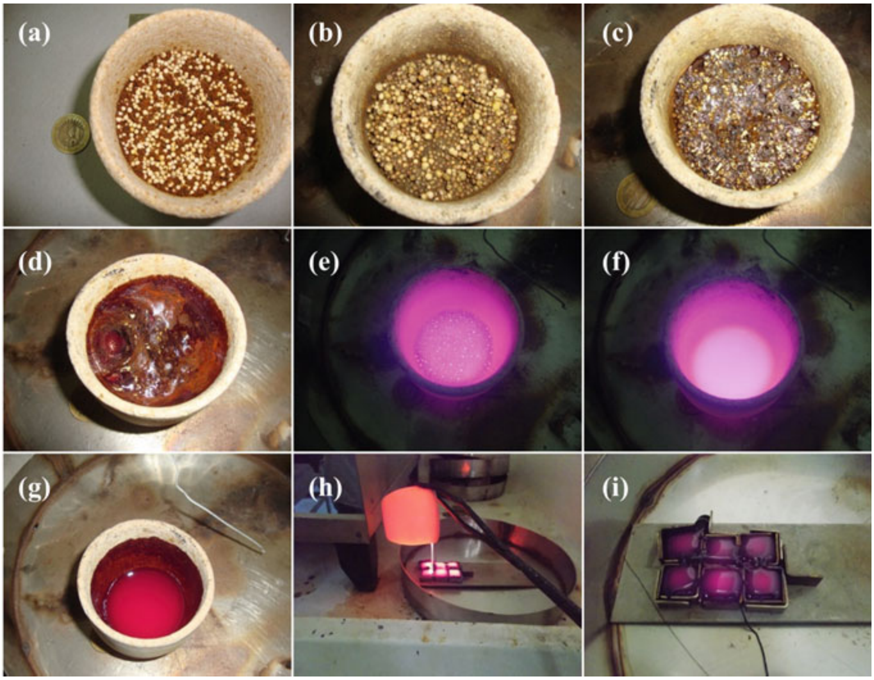


Fig. 2 **a** 25 °C (frit + nitrates), **b** 400 °C, **c** 600 °C, **d** 800 °C, **e** 1000 °C (immediate, gas bubbles are visible), **f** 1000 °C (after soaking for 5 h, observed homogenous melt), **g** molten glass ready for pouring, **h** glass pouring in SS mold, and **i** SVWP glass

Table 2 Salient features of VWPs

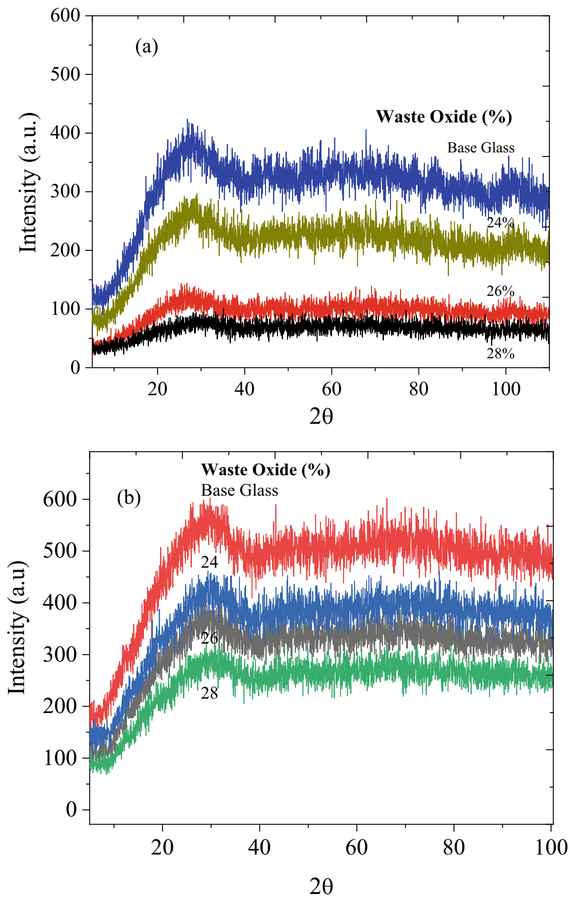
S. no	Characteristics	BG	VWP-S1			VWP-S2			VWP-S3		
% WO		0	24	26	28	24	26	28	24	26	28
01	T_p (°C)	975	950	950	950	950	950	950	970	970	960
02	ρ (g/cm^3)	2.46	2.76	2.83	2.92	2.47	2.54	2.62	2.69	2.77	2.82
03	T_g (°C)	575.5	550.0	548.5	545.6	554.8	549.9	547.1	565.6	555.3	551.6
04	Nature	Amorphous (solid)									
05	Leach rate (10^{-6} g/cm^2·day) based on Na-ion										
	7 days	–	–			1.27	1.39	1.64	7.21	7.59	7.99
	28 days	–	0.85	0.97	0.82	0.39	0.43	0.47	0.31	0.30	0.42
06	Homogeneity	Homogeneous									

The pouring temperature of VWP-S3 is in the range of 960–970 °C; the marginal increase is directly related to the content of the modifier in the composition (Table 1). S3-$NaNO_3$ content is almost 50% less than S1 and S2. Nevertheless, the pouring temperature, 960–970 °C, is within the operational range of the JHC Melter.

The density (ρ) of the glass products obtained using Archimedes' principle from different batches was checked and found to be in the 2.4–2.9 g/cm^3 range. This narrow limit indicates the uniformity in the preparation of glasses and consistency in the dispersion of the elements in the vitreous melt. Further, the density increase may be attributed to the reduction of free volume due to the transformation of BO_3 to BO_4 units in the presence of Na_2O. Typically, in the glass matrix, the Si–O-Si bond starts to dislodge when the Na_2O/B_2O_3 ratio is 0.5–1, hence, a more significant number of NBO forms, which attributes the transformation of BO_3 to BO_4. Beyond ($Na_2O/B_2O_3 > 1.0$), the transformation of BO_3 to BO_4 is complete [15].

The X-ray diffraction results of base glass and VWP-S1 and S2 are shown in Fig. 3a and b. The diffraction pattern shows that the prepared SVWPs are amorphous. The absence of crystallinity within the formed vitreous mass indicates that the base glass accommodates the composition studied well (Table 1). Also, it reveals that there was no devitrification during the cooling of the melt.

Fig. 3 Phase analysis (by using XRD) of the VWP—**a** S1 and **b** S2



The DTA and DSC traces for VWP-S2 and S3, respectively, are shown in Fig. 4. The measurement of the VWP's glass transition temperature (T_g) has practical importance related to devitrification. Devitrification is the spontaneous formation of scattered microscopic crystals in the glass matrix. Typically, after the molten glass is solidified in the SS canister, the interior temperature is higher than the wall due to radioactive decay, which may cause devitrification when T_g is lower than the temperature of VWP during storage/disposal conditions. Though devitrification is a time- and temperature-dependent phenomenon, the VWP composition also plays a vital role; hence, the controlled composition of HLW or base glass matrix may avoid devitrification. The measured T_g values from DTA or DSC studies range from 540 to 560 °C. Figure 5 shows the role of B_2O_3/Na_2O on T_g. The T_g varies from 565 to 545 °C with the Na_2O/B_2O_3 ratio of 0.32 to 0.70, which reveals that the transformation of BO_3 to BO_4 is a transition. Further, the results depict the role of Na_2O and

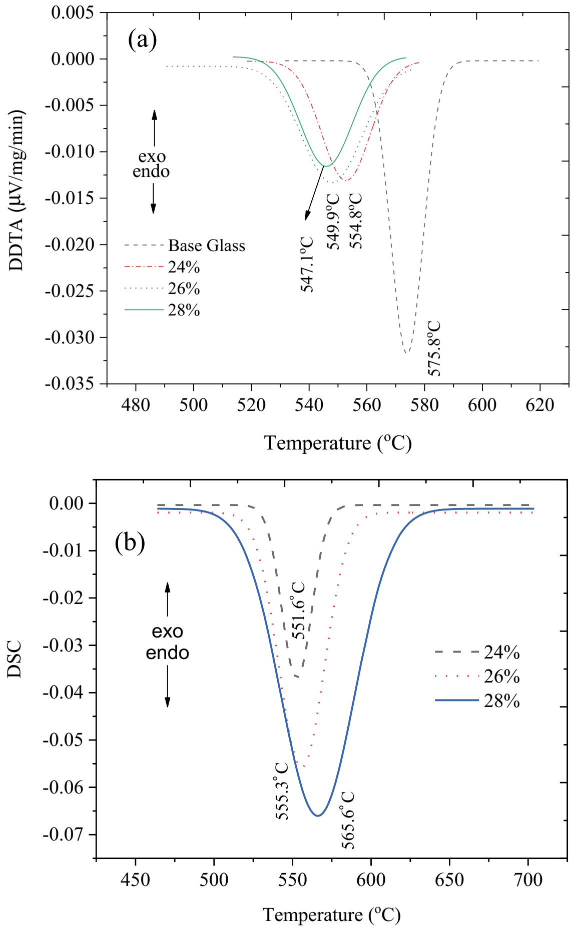


Fig. 4 T_g of the VWP—**a** S2 and **b** S3

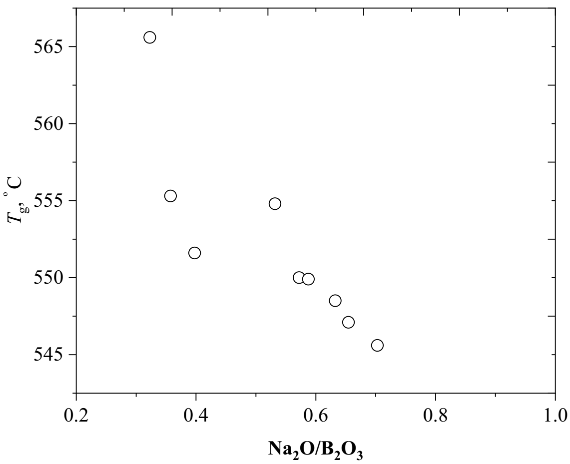


Fig. 5 Role of B_2O_3/Na_2O on T_g of the VWP

show that S1 and S2 may have more non-bonded oxygen (NBO) than S3. However, the measured T_g values are comparable with the international literature [7] and are within the acceptable range for optimized waste loading.

Optical microscope analysis showed surface homogeneity of the VWP-S2 (Fig. 6). No crystalline or inclusion or liquid phase separations were noticed. The images (Fig. 6) further support the above findings of phase analysis (amorphous) and T_g (sufficient to avoid devitrification-crystallization).

Chemical durability is one of the most vital characteristics of the radionuclide-conditioned product. ASTM C1285-21, product consistency test (PCT), is used worldwide to test glass and glass–ceramic forms of HLW and other hazardous wastes. PCT-A and PCT-B provide data that helps evaluate the chemical durability of glass waste forms as measured by elemental release. In other words, the outcome of PCT-A can be used to evaluate the chemical durability of the glass waste forms during production, and PCT-B can be used to assess under various leaching conditions. The chemical durability of the conditioned products was studied by measuring sodium (Na) leaching behaviors. Na being monovalent and smaller in ionic size than other metal ions, Na's leach rate can be more rapid than other metals. The leach rate concerning Na was calculated by using the following expression: $LR_{Na} = \frac{C_{Na}}{C_0} \times \frac{W_0}{S \times t}$ (g cm^{-2} day^{-1}).

Where LR_{Na} is the leach rate with respect to the release of Na-ion (g cm^{-2} day^{-1}), C_{Na} is the amount of Na-ion leached out (g), C_0 is the amount of Na-ion in the sample (g), W_0 is the weight of the sample (g), S is the surface area of the sample (cm^2), and t is the time interval of leaching (days). Figure 7a and b shows the leach rate for Na-ion as a function of time over 28 days for VWP-S1 and S3, respectively. Rapid release of Na^+ ion, called diffusion/interdiffusion—from day 1 to 6, infers that the ion exchange process is operative between Na^+ ion with H^+/H_3O^+ from the contacting solution, leaving the glass's near-surface depleted to the element. Na^+ loss in the remaining day from 6 is due to the slower breakdown of the glass network by hydrolysis [16]. The leach rate (10^{-5}–10^{-6} g/cm^2·day) of PCT-A and B tests and T_g (540–565 °C) were acceptable and on par with international recommendations