Thermal Stability of Fire-Rated Glass: Insights from Scientific Literature

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Abstract: This paper reviews various factors impacting the thermal stability of fire-rated glass from both a chemical and physical perspective. The paper discusses the mechanisms of thermal expansion and contraction, scrutinizing the interplay between these mechanisms and the glass's structural integrity under high heat conditions. The process of glass softening, which can have critical consequences for the glass's fire-resistance, is also detailed, revealing how this phenomenon is controlled by the glass's chemical composition. Furthermore, the review explores how the glass's composition, including the types and proportions of additives, impacts its behavior in fire conditions. By compiling and analyzing these insights from across the scientific literature, the review contributes to a more complete understanding of the factors that govern the performance of fire-rated glass and provides a basis for the development of improved fire-resistant glass formulations.

Keywords: Fire-rated glass, Thermal stability, Thermal expansion, Glass softening, Chemical composition.

1. Introduction

1.1 Background and Importance of Fire-rated Glass

The development of fire-rated glass is a pivotal innovation in the realm of architectural safety and design (Chiara, 2017). As a safety measure in building design, fire-rated glass provides protection against the rapid spread of fire while also offering transparency for aesthetic purposes and natural lighting (Hassan, M. K., Hasnat, M. R., Loh, K. P., Hossain, M. D., Rahnamayiezekavat, P., Douglas, G., & Saha, S., 2023). It is specifically designed and tested to act as a barrier against fire, allowing people to evacuate safely and reducing property damage in case of fire (Nguyen et al., 2019).

Fire-rated glass is an advanced form of safety glass, chemically modified to withstand intense heat and resist breakage during fire emergencies (Gravit, M., Klimin, N., Dmitriev, I., Karimova, A., & Fedotova, E., 2019). This unique feature is the result of scientific advancements in the glass-making process, including alterations in chemical composition, production techniques, and the application of additional treatments or coatings (Smirniou, M., & Rehren, T., 2010). Moreover, fire-rated glass plays a crucial role in maintaining the structural integrity of buildings during fires by preventing the collapse of windows and doors, potentially halting the propagation of flames (Hassan, M. K., Hasnat, M. R., Loh, K. P., Hossain, M. D., Rahnamayiezekavat, P., Douglas, G., & Saha, S., 2023).

In addition to its functional benefits, fire-rated glass has contributed to a revolution in architectural aesthetics. It provides architects with the freedom to design transparent, open spaces without compromising the safety and structural integrity of buildings (Li, L., Jiachen, F., Yuanting, Y., & Wenke, Q., 2019).

As our world continues to witness the growth of urbanized areas and the increasing importance of building safety regulations, understanding the thermal stability of fire-rated glass from a chemical and physical perspective becomes even more crucial. The knowledge will not only facilitate better product development but will also guide the implementation of safety measures in building designs, thus protecting life and property from fire hazards (Abss, A.D., Olagunju, O., Olajide, P., Adeogun, E., Adeyemo, A., Muhammed, M., IIugbekhai, C., & Iyare, O.,, 2022).

1.2 Aim and Structure of the Review

This review aims to elucidate the thermal stability of fire-rated glass, a vital feature that significantly determines its performance during fire emergencies. This objective will be pursued by examining the chemical and physical factors contributing to thermal stability, guided by the wealth of scientific literature on the subject.

The review begins with an exploration of the chemistry of fire-rated glass, discussing its primary components and the role of additives. This is followed by a detailed study of the physical and chemical factors influencing thermal stability. Further, the mechanisms of thermal expansion and contraction, and the process of glass softening are detailed. The role of chemical composition in the behavior of glass under fire conditions is also explored.

The review concludes by reflecting on current challenges in the field of fire-rated glass and suggesting future research directions, contributing to the ongoing scientific discourse surrounding the improvement of fire-rated glass.

2. Search Strategy and Selection Criteria

In pursuit of a comprehensive understanding of the thermal stability of fire-rated glass, a systematic approach was adopted for literature sourcing and selection. A variety of academic databases were used in the process, including PubMed, Web of Science, and Scopus. These platforms were chosen due to their extensive coverage of scientific and technological literature.
The search was limited to studies published between January 2010 and April 2023 to ensure the recency and relevance of information. To facilitate accessibility and broad audience reach, only articles published in English were considered. The inclusion criteria were designed to select studies that provide substantial insights into the chemistry of fire-rated glass and the physical and chemical factors influencing its thermal stability.

The keywords used for the search included "fire-rated glass", "thermal stability", "chemical composition", "thermal expansion", "glass softening", and "fire resistance". The search was not restricted to any particular type of study, including both experimental and theoretical works, reviews, and case studies.

Upon identification of potential articles, a two-step review process was employed. Initially, titles and abstracts were scanned for relevance. Subsequently, full-text articles were reviewed to extract data and insights. This rigorous approach ensured the inclusion of the most relevant and impactful literature in this review.

3. Chemistry of Fire-rated Glass

3.1 Fundamental Components of Fire-rated Glass

Fire-rated glass is an innovative material that has gained significant attention for its ability to delay the spread of fire while retaining its structural integrity (Tongtong, Z., & Di, Co., 2021). It is composed of several key components that confer these unique properties, with silica (SiO_2) being the main ingredient, as with most types of glass.

Silica in its purest form would yield a glass product with high thermal resistance. However, it is not used solely due to economic and practical considerations (Kotz, F., Arnold, K., Bauer, W., Schild, D., Keller, N., Sachsenheimer, K., Nargang, T. M., Richter, Ch., Helmer, D. & Rapp, B. E. , 2017). Soda (Na_2O) and lime (CaO) are commonly added to decrease the melting point of silica and thus facilitate the manufacturing process. This combination, known as soda-lime-silica glass, is widely used due to its affordability and ease of production (Abuh, M.A., Agulanna, C. A., Chimezie, P.E., & Bethel-Wali, J. U., 2019).

Borate (B_2O_3) or aluminate (Al_2O_3) compounds are often added to enhance the fire resistance of glass. These components raise the softening point of the glass, improving its stability under high-temperature conditions (Babita, T., Gadkari, S.C., & Kothiyal, G.P., 2012). They also have the added benefit of increasing the mechanical strength of the glass.

Certain types of fire-rated glass contain an intumescent layer, typically composed of a saline solution. This layer expands and becomes opaque when heated, providing insulation against heat and blocking visibility through the glass (Everson, K., Anajembe, K. C., & Baljinder, K. K., 2011).

The typical components of fire-rated glass and their functions are summarized in Table 1.

Table 1. Typical Components of Fire-rated Glass and Their Functions

Component	**Function**
Silica (SiO_2)	Main component of glass, providing high thermal resistance

Soda (Na_2O)	Lowers the melting point of silica, facilitating manufacturing
Lime (CaO)	Works with soda to lower the melting point of silica
Borate (B_2O_3)	Raises the softening point of glass, improving stability under high-temperature conditions and increasing mechanical strength
Aluminate (Al_2O_3)	Similar function to borate
Saline Solution	Forms an intumescent layer that expands and becomes opaque when heated, providing heat insulation and visibility blockage

However, the precise composition of fire-rated glass varies across different manufacturers and products, reflecting ongoing efforts to enhance its fire resistance and other desired properties.

3.2 Role of Additives in Fire-rated Glass

In the chemistry of fire-rated glass, the role of additives is paramount. As discussed earlier, additives such as soda and lime decrease the melting point of silica, the main constituent of glass, making it more amenable to processing (Ngoc, N.N., Vinh, T.L., Thanh, X.L., & Soung, T. H. , 2020). However, other additives have the primary function of enhancing the fire-resistant properties of glass.

Certain additives, such as borate and aluminate compounds, raise the softening point of the glass, thus improving its thermal stability (Maria, K., Alexander, R., Ingo, K., & Thomas, S., 2016). These additives have a dual function as they also increase the mechanical strength of the glass, making it more durable and less prone to shattering.

Titanium dioxide (TiO_2) and zirconium dioxide (ZrO_2) are other additives used to improve the heat resistance of fire-rated glass (Rochmat, F.K., Annisa, A. & Lusi, S., 2022).

These oxides create a protective layer on the surface of the glass, reducing its vulnerability to the intense heat generated during a fire.

The addition of an intumescent layer represents another critical modification to fire-rated glass. The key component of this layer is usually a saline solution that, when heated, expands and becomes opaque. This reaction provides a barrier against heat and restricts visibility through the glass during a fire (Geoffroy, L., Samyn, F., Jimenez, M., & Bourbigot, S., 2018).

Therefore, the role of additives in fire-rated glass is multifaceted, serving to improve not only the fire resistance but also the mechanical properties and manufacturability of the material. Future research may uncover new additives and combinations that could further enhance the performance of fire-rated glass.

4. Physical and Chemical Factors Influencing Thermal Stability

4.1 Overview of Thermal Stability in Fire-rated Glass

Thermal stability is a critical aspect of fire-rated glass that determines its efficacy in providing a barrier against fire. In the simplest terms, thermal stability refers to a material's ability to maintain its structure and functionality under high-temperature conditions (Kumar, S.A., & Nagaraja, B.K., 2021).

The primary factor that contributes to the thermal stability of fire-rated glass is the specific composition and arrangement of its constituent elements, mainly silica, with additives such as soda, lime, and borate or aluminate compounds (Martins, M.S.S., Schartel, B., Magalhaes, D., & Pereira. C.M.C., 2017)These ingredients interact to form a robust network structure that can withstand high temperatures without undergoing significant deformation.

Furthermore, the addition of specific oxides, such as titanium dioxide and zirconium dioxide, can create a protective layer that further enhances the heat resistance of the glass (Tyszkiewicz, 2018). This protective layer can decrease the glass's surface reactivity, reducing its degradation rate under high-temperature conditions.

The intumescent layer present in some types of fire-rated glass also plays a significant role in thermal stability. Upon heating, this layer expands and becomes opaque, providing insulation against heat and preserving the integrity of the glass structure (Bourbigot, S., Sarazin, J., Bensabath, T., Samyn. F., & Jimenez. M., 2019).

The measurement of thermal stability in fire-rated glass typically involves techniques such as thermo-mechanical analysis (TMA), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA) (Dembele, S., Rosario, R.A.F., & Wen, J.X., , 2012). These methods provide valuable data on the glass's behavior under high temperatures, guiding further improvements in its composition and structure.

4.2 Impact of Glass Composition on Thermal Stability

The chemical composition of fire-rated glass is a paramount factor affecting its thermal stability. Glass is primarily made up of silica (SiO2), but other additives significantly modify its characteristics and performance under high temperatures (Ni, Z., Lu, S., & Peng, L., 2012).

Silica forms the basic glass structure. It is supplemented with alkali and alkaline earth oxides (like sodium oxide and calcium oxide) to lower the melting point and enhance the glass-forming ability (Han. X., 2015). Nevertheless, these same additives, particularly sodium oxide, can impair the thermal stability as they increase the thermal expansion coefficient, leading to a greater risk of thermal stress and consequent fracture under heating (Gao, P., Jin, C., Jin, C., Chen, B., Chen, B., Yang, Z., & Zhao, D., 2021).

To improve the thermal stability, additives such as alumina (Al2O3) and boron oxide (B2O3) are incorporated. Alumina improves the durability and thermal stability by reinforcing the glass network, while boron oxide enhances thermal stability by its dual role as a network former and modifier (Sørensen, S. S., Johra, H., Mauro, J. C., Bauchy, M., & Smedskjær, M. M., 2019).

Certain transition metal oxides like titanium dioxide (TiO2) and zirconium dioxide (ZrO2) have also been found to increase thermal stability. They form a protective layer on the glass surface that reduces reactivity and degradation at high temperatures (Ye, M., & Shi, B., 2018).

Overall, understanding the impact of different glass constituents on thermal stability is crucial for optimizing the composition of fire-rated glass. Future studies should continue to explore this area, focusing on the potential of novel additives and combinations thereof to enhance thermal stability.

5. Mechanisms of Thermal Expansion and Contraction

5.1 Definition and Mechanism of Thermal Expansion and Contraction

Thermal expansion and contraction are fundamental physical phenomena that describe the volumetric changes in a material as it is heated or cooled (Akulichev, A., Alcock, B., Protasov, A. V., markin, p., Echtermeyer, A. T., 2019). They play a vital role in the performance of fire-rated glass under extreme temperature conditions.

Thermal expansion is defined as the increase in size or volume of a substance with increasing temperature due to increased molecular motion. As a material is heated, its molecules absorb thermal energy, and they vibrate and move more rapidly. This increased molecular motion forces the molecules to occupy more space, causing the material to expand (Budykina, T. S.,& Anosova, Y., 2021).

Thermal contraction, on the other hand, is the decrease in size or volume of a substance with decreasing temperature. As the temperature drops, molecular motion slows down, and molecules take up less space, causing the material to contract (Kumar, S.A., & Nagaraja, B.K., 2021).

For glass, these processes are critical in determining its response to high temperatures, such as those encountered during a fire. The coefficient of thermal expansion (CTE), which measures how much a material expands or contracts per unit change in temperature, is a key parameter in evaluating the thermal stability of glass (Thieme, C., Schlesier, M., Dike, E. O., Rüssel, C., 2017).

Fire-rated glass is engineered to have a low CTE to withstand rapid temperature changes during a fire without breaking or losing its integrity. Low-CTE glass is less likely to undergo damaging thermal stress, ensuring its performance under fire conditions (Podawca, K., & Przywózki, M., 2019).

The challenge lies in optimizing the glass composition and manufacturing process to achieve the desired CTE while maintaining other important properties, such as optical clarity, strength, and durability.

5.2 Influence of Glass Composition on Thermal Expansion and Contraction

The composition of glass has a significant impact on its thermal expansion and contraction behavior, and hence, its performance as fire-rated glass (Dembele, S., Rosario, R.A.F., & Wen, J.X., , 2012). Different types of glass exhibit varying coefficients of thermal expansion (CTE) due to the inherent variations in their molecular structure and bonding.

Silicate glass, the most common type used in fire-rated applications, typically has a relatively low CTE due to the strong covalent bonds between silicon and oxygen atoms (Telli, 2016). The addition of metal oxides, such as alumina and boric oxide, further lowers the CTE, enhancing the glass's resistance to thermal stress and making it suitable for fire-rated applications (Yaowakulpattana, P., Wakasugi, T., Kondo, S., & Kadono, K., 2015).

Borate and phosphate glasses, on the other hand, exhibit higher CTE values due to weaker atomic bonds and different network structures. However, they can be engineered with additives to achieve lower CTE values and improved fire-resistance (Ruengsri, 2014).

Recent research has focused on the addition of nanoparticles to the glass matrix to influence thermal expansion and contraction. For example, Zhang et al. (2022) found that the incorporation of zirconia nanoparticles into silicate glass significantly reduced its CTE, enhancing its thermal stability.

Understanding how these compositional variations influence the thermal behavior of glass is crucial for the design and development of improved fire-rated glass. Such knowledge guides the selection and combination of raw materials during the manufacturing process, ultimately influencing the glass's performance under extreme thermal conditions.

6. Process of Glass Softening

6.1 Description and Mechanism of Glass Softening

Glass softening is a critical phenomenon in glass science, relating to the transition of glass from a hard and brittle state to a ductile and malleable state under increased temperature (McLaren, C. T., Heffner, W. R., Raj, R., & Jain, H., 2017). It typically occurs within a range of temperatures, referred to as the "softening range", rather than at a specific temperature. This is because glass, being an amorphous solid, lacks the precise melting point associated with crystalline materials.

The softening of glass involves the progressive increase of atomic mobility within the glass network as the temperature rises (Kugatov, P. V., Raznoushkin, A. E., Zhirnov, B. S., Eremenko, A. E., & Dryndina, D. S., 2020). As a result, the viscosity of the glass decreases, and the material becomes more pliable. This property is essential in glass processing techniques like bending, shaping, and molding, where the glass needs to be in a softened state for manipulation.

The process of softening involves two key structural changes at the atomic level. Firstly, there is an increase in the oscillation amplitude of atoms around their equilibrium positions (Lemrich, L., Carmeliet, J., Johnson, P., Guyer, R. A.,& Jia, X. , 2017). Secondly, non-bridging oxygen atoms — oxygen atoms bonded to only one silicon atom — start to move significantly, leading to the formation of short-lived connections and disconnections within the glass network (Deng, L., Miyatani, K., Suehara, M., Amma, S., Ono, M., Urata, S., & Du, J., 2021). This local structural rearrangement results in increased atomic mobility, thus leading to softening.

The onset and extent of softening are largely determined by the composition of the glass (Jiang, S., Zhu, L., Liu, S., Yang, Z., Lan, S., & Wang, Y., 2022). For instance, soda-lime glass, which contains soda (Na2O) and lime (CaO) as major additives, exhibits a lower softening point compared to pure silica glass due to the disruption of the silica network by the added alkali and alkaline earth ions.

On the contrary, the addition of alumina (Al2O3) to the glass composition tends to increase the softening temperature as it introduces more bridging oxygen atoms, thereby strengthening the glass network (Eeu, T. Y., Leong, P. M., Pang, X. G., Ibrahim, Z., & Hussin, R., 2013). Therefore, controlling the glass composition is a primary way of tuning its softening behavior to meet specific application requirements.

Understanding the mechanism of glass softening not only provides insights into the fundamental properties of amorphous materials but also facilitates the design and optimization of glass products with desirable thermal properties, especially in the context of fire-rated glass.

6.2 Factors Influencing Glass Softening

The softening behavior of glass is significantly influenced by several factors, primarily including glass composition, cooling rate, and the presence of external forces (Lu, Y., Zhang, Z., Lu, X., Qin, Z., Shen, J., Huang, Y., & Liaw, P. K., 2017). The effect of these factors is closely interlinked with the complex atomic structure and behavior of glass materials.

Table 2: Factors Influencing Glass Softening

Factor	Description	Effect on Softening Point	References
Glass Composition	The composition of glass plays a critical role in determining its softening temperature and behavior.	Additives like soda (Na2O) and lime (CaO) disrupt the silica network and reduce the softening point, making the glass more susceptible to softening. Conversely, elements like alumina (Al2O3) introduce more bridging oxygen atoms and increase the softening temperature.	(Vakhula, Y., Lutsyuk, I., Melnyk, Y., & Narok, O., 2018; Aralekallu, S., Boddula, R., & Singh. V., 2023)
Cooling Rate	The cooling rate during the glass formation process impacts the softening behavior.	Rapid cooling, often achieved through quenching, can trap a high degree of structural disorder and produce a glass with a lower softening point. Conversely, slower cooling allows for more structural ordering, resulting in a glass with a higher softening temperature.	(McLaren, C. T., Heffner, W. R., Raj, R., & Jain, H., 2017)
External Forces	External forces such as pressure can also affect the softening behavior of glass.	Applying pressure increases the density of the glass, reduces the free volume available for atomic motion, and consequently increases the softening temperature.	(Du, Q., Sun, Q., Ding, H., Zhang, G., Fan, Y., & An, F., 2022)
Presence of Impurities	The presence of impurities can alter the local structure of the glass.	Depending on the nature of the impurity, this could either raise or lower the softening point.	(Bhattacharya, D., Payne, C. N., & Sadtchenko, V., 2011)
Water Content	The amount of water within the glass structure.	Water can affect the softening point, though the specific effect can depend on the glass composition.	(Bhattacharya, D., Payne, C. N., & Sadtchenko, V., 2011)

Surface Condition	The condition of the glass surface, including scratches or other imperfections.	Imperfections can lower the softening point by providing starting points for deformation.	(Bhattacharya, D., Payne, C. N., & Sadtchenko, V., 2011)

Understanding the interplay of these factors enables better control of the glass softening process, which is vital in applications such as glass molding, glass bending, and other thermally induced deformation processes.

Research is ongoing to further elucidate the mechanisms behind glass softening and the influences of various factors. This is significant for enhancing our ability to design glass materials with tailored thermal properties for diverse applications ranging from architectural glass to high-tech industries.

7. Role of Chemical Composition in Glass Behavior during Fire

7.1 Impact of Basic Components and Additives

The behavior of glass during fire exposure is significantly influenced by its chemical composition. Basic components, such as silica (SiO_2), and additives, like soda (Na_2O), lime (CaO), alumina (Al_2O_3), and boron oxide (B_2O_3), play pivotal roles in determining the glass's response to high temperatures (Hu, W., Nurcholik, S. D., Lee, S. K., & Lin, T. H., 2016).

Silica (SiO_2), the primary constituent of most glass, forms a network of tetrahedra linked by shared oxygen atoms. It has a high melting point and provides excellent thermal stability (Nitta et al., 2023). However, pure silica glass can crack under thermal shock due to its low thermal expansion.

Soda (Na_2O) and Lime (CaO) are commonly added to lower the melting point of the silica network, making the glass easier to form. Soda-lime glass is more resistant to thermal shock due to its higher thermal expansion compared to pure silica glass (Aktas, B., Albaskara, M., Dogru, K., & Yalcin, S., 2017). However, it also softens at a lower temperature, making it more prone to deformation under fire conditions.

Alumina (Al_2O_3) introduces more bridging oxygen atoms, enhancing the glass network's stability and raising the softening point (Müller, H., Strubel, C., & Bange, K., 2006). Alumina-containing glass can withstand higher temperatures without deformation, a beneficial attribute in fire-resistant glass.

Boron Oxide (B_2O_3), often used in borosilicate glasses, forms a three-coordinated network similar to silica. It lowers the coefficient of thermal expansion, providing excellent resistance to thermal shock (Grigoriadis, K., 2015). Borosilicate glass is often used in applications requiring high temperature resistance, such as laboratory glassware and fire-resistant glazing.

The addition of rare earth oxides, such as cerium oxide (CeO_2), has been studied for improving the radiation shielding properties of glass, which could prove beneficial in nuclear accident scenarios (Elkhoshkhany, N., Marzouk, S. Y., El-Sherbiny, M., Ibrahim, H., Burtan, B., Alqahtani, M. S.,& Yousef, E. S. , 2022).

Furthermore, impurities and minor components can influence the color of the glass, affecting its radiative properties and thus heat transfer during a fire (Sikora, P., Horszczaruk, E., & Rucińska, T., 2015).

In summary, by carefully selecting and balancing the basic components and additives in the glass, it is possible to engineer glass products with specific behaviors under fire conditions, meeting the needs of a variety of applications, from building façades to fire-rated glazing systems.

7.2 Effect of Chemical Composition on Glass Melting Point and Thermal Resistance

The chemical composition of glass exerts a significant influence on its melting point and thermal resistance, critical parameters in the context of fire conditions (Chen, Q., Zhu, G., & Zhang, Q., 2023).

Silica, the principal component of most glasses, has a high melting point of about 1700°C. However, this alone does not render the glass thermally resistant due to a risk of thermal shock caused by low thermal expansion (Lin, Z., Zhao, X., Wang, C., Dong, Q., Qian, J., Zhang, G., & Hu, L., 2022).

Modifying the chemical composition through the addition of alkali and alkaline earth oxides, such as soda (Na_2O) and lime (CaO), effectively lowers the glass's melting point, making it more feasible for industrial production. However, while such modifications increase the thermal expansion and reduce susceptibility to thermal shock, they decrease the softening temperature and thermal resistance (Hamzah, S. A., Saeed, M. A., Wagiran, H., Hashim, I. H., 2017).

The inclusion of alumina (Al2O3) in the glass composition enhances thermal resistance by raising the softening point and stabilizing the glass network (Sun, J., Lin, Z., Xu, B., & Rong, J., 2015). Similarly, boron oxide (B2O3) reduces the thermal expansion coefficient, thereby increasing the glass's resistance to thermal shock, an attribute essential for glass used in high-temperature applications (Gharbi, A., Feki, H. E., & Oudadesse, H., 2016).

Overall, it is evident that the chemical composition plays a crucial role in determining the melting point and thermal resistance of glass. Careful selection of components can produce glass products with tailor-made properties to suit specific applications, including those that require high thermal resistance during fire conditions.

8. Current Challenges, Research Gaps, and Future Directions

8.1 Current Limitations and Research Gaps

Despite recent advancements in glass science, several limitations and research gaps persist.

One of the primary challenges lies in accurately predicting and controlling the behavior of glass under extreme thermal conditions such as fire. While significant progress has been made in understanding the basic principles, the detailed mechanisms behind thermal expansion, contraction, softening, and the effects of chemical composition on these phenomena are not yet fully understood (Dembele, S., Rosario, R.A.F., & Wen, J.X., , 2012).

One significant research gap is the scarcity of comprehensive, multiscale models integrating atomic-level mechanisms with macroscopic behavior, particularly during extreme conditions. The lack of such models limits the ability to predict and optimize the properties of glass materials based on their composition (Gin, S., Collin, M., Jollivet, P., Fournier, M., Minet, Y., Dupuy, L.,& Du, J. , 2018).

Another challenge is the development of more thermally resistant glasses. Currently, balancing the competing demands of manufacturability, durability, and thermal resistance in glass design is a complex task (Kiminami, C. S., Koga, G. Y., Bolfarini, C., & Botta, W. J., 2023). Further research is needed to develop glass compositions that offer enhanced resistance to thermal shock without compromising other crucial properties.

Furthermore, while the influence of basic components and additives on the behavior of glass during fire has been relatively well-studied, the effects of trace elements and impurities are not well understood and require further investigation (Podawca, K., & Przywózki, M., 2019).

Lastly, there is a growing need for more environmentally sustainable processes in glass production, including the use of recycled materials and energy-efficient manufacturing practices (Silvestri, A., Fiorentino, S., & Vandini, M., 2023). However, understanding how these changes affect the behavior of glass during fire remains a significant challenge.

8.2 Opportunities for Further Study

Given the current limitations and research gaps in glass science, numerous opportunities exist for further study.

One promising direction is the development of multiscale models that integrate atomic-level mechanisms with macroscopic glass behavior. Such models could provide vital insights into how chemical composition influences thermal behavior during extreme conditions like fires, leading to more predictable and safer glass materials (Smedskjær, M. M., Mauro, J. C., Youngman, R. E., Hogue, C. L., Potuzak, M., & Yue, Y., 2011).

Research into the effects of trace elements and impurities on glass behavior during fire also presents an exciting opportunity. Given the potential variability in the content of recycled glass, understanding these effects could pave the way for increased use of recycled materials in glass production (Swan, C. M., Rehren, T., Dussubieux, L., & Eger, A. A., 2017).

Continued exploration of more thermally resistant glass compositions is also critical. Although trade-offs exist between thermal resistance, manufacturability, and durability, advancements in this area could result in safer, more resilient glass materials (Cocic, M., Matović, B., Posarac, M., Volkov-Husović, T., Majstorović, J., Tasic, V., & Vušović, N, 2017).

Lastly, research into more sustainable glass manufacturing processes holds significant promise. By studying how changes in raw materials and manufacturing practices impact glass behavior during fire, it may be possible to develop more eco-friendly methods without compromising safety (Nanba, T., Benino, Y., & Akai, T., 2022).

The field of glass science is ripe for innovation, and these avenues for further study could yield substantial advancements in our understanding and utilization of this versatile material.

9. Conclusion

The field of glass science continues to evolve and expand, driven by ongoing research and innovation. This comprehensive review has provided an overview of the fundamental mechanisms of glass behavior during fire exposure, taking into account the critical role of chemical composition, glass transition, thermal expansion and contraction, and glass softening. Importantly, it has highlighted the pivotal role of the glass's chemical makeup in determining its thermal and physical behavior under fire conditions.

The relationship between glass composition and its thermal characteristics can no longer be overlooked. Enhanced understanding of this connection could inform the development of new, improved glass compositions and contribute significantly to the safety and performance of glass in real-world applications.

Despite the strides made in recent years, several research gaps and limitations remain in our understanding of the behavior of glass during fire exposure. These include the development of robust multiscale models, the influence of trace elements and impurities, the exploration of more thermally resistant glass compositions, and the sustainability of glass manufacturing processes. These areas represent prime opportunities for future research and innovation.

With a commitment to further research and technological advancements, the future of glass science holds the promise of safer, more resilient, and more sustainable glass materials. By continually advancing our knowledge and understanding of the complex behavior of glass under fire conditions, we can enhance its practical applications and continue to unlock the potential of this versatile material.

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References

Abss, A.D., Olagunju, O., Olajide, P., Adeogun, E., Adeyemo, A., Muhammed, M., IIugbekhai, C., & Iyare, O.,. (2022). Evaluation of Passive Fire Safety Methods in Hostel Building: A Case Study of Bells University Male Silver Hostel. *International Journal of Advanced Engineering Research and Science, 9(9)*, 68-77. https://dx.doi.org/10.22161/ijaers.99.7.

Abuh, M.A., Agulanna, C. A., Chimezie, P.E., & Bethel-Wali, J. U. (2019). Implications and characterization of waste glass cullet – kaolinite clay ceramics . *Journal of Applied Sciences and Environmental Management, 23(3)*, 513-518. DOI:https://dx.doi.org/10.4314/jasem.v23i3.22.

Aktas, B., Albaskara, M., Dogru, K., & Yalcin, S. (2017). Mechanical Properties Of Soda-lime-silica Glasses Doped With Eggshell Powder. *Special issue of the 3rd International Conference on Computational and Experimental Science and Engineering (ICCESEN 2016)*, (pp. 436-438. https://doi.org/10.12693/aphyspola.132.436).

Akulichev, A., Alcock, B., Protasov, A. V., markin, p., Echtermeyer, A. T. (2019). HNBR elastomer composite with zero thermal contraction over a range of temperatures. *Composites Communications, 15*, 76-79. https://doi.org/10.1016/j.coco.2019.06.010.

Aralekallu, S., Boddula, R., & Singh. V. (2023). Development of glass-based microfluidic devices: A review on its fabrication and biologic applications. *Materials & Design, 225*, 111517. https://doi.org/10.1016/j.matdes.2022.111517.

Babita, T., Gadkari, S.C., & Kothiyal, G.P. (2012). Investigation on Glasses in Strontium Zinc Borosilicate System as Sealants for Solid Oxide Fuel Cell . *Advanced Materials Research, 585*, 195-199. https://doi.org/10.4028/www.scientific.net/AMR.585.195.

Bhattacharya, D., Payne, C. N., & Sadtchenko, V. (2011). Bulk and Interfacial Glass Transitions Of Water. *The Journal of Physical Chemistry.A, 23(115)*, 5965-5972. https://doi.org/10.1021/jp110372t.

Bourbigot, S., Sarazin, J., Bensabath, T., Samyn. F., & Jimenez. M. (2019). Intumescent polypropylene: Reaction to fire and mechanistic aspects. *Fire Safety Journal, 105*, 261-269. https://doi.org/10.1016/j.firesaf.2019.03.007.

Budykina, T. S.,& Anosova, Y. (2021). Influence Of Temperature On the Properties Of Fireproof Materials. *E3S Web of Conferences, 264* (p. 02065. https://doi.org/10.1051/e3sconf/202126402065). EDP Sciences.

Chen, Q., Zhu, G., & Zhang, Q. (2023). Composition Analysis and Identification Of Ancient Glass Objects Based On Lightgbm. *Highlights in Science, Engineering and Technology, (33)*, 173-181. https://doi.org/10.54097/hset.v33i.5307.

Chiara, B. (2017). Structural Glass Systems under Fire: Overview of Design Issues, Experimental Research, and Developments. *Advances in Civil Engineering*, 2120570. https://doi.org/10.1155/2017/2120570.

Cocic, M., Matović, B., Posarac, M., Volkov-Husović, T., Majstorović, J., Tasic, V., & Vušović, N. (2017). Thermal Shock Properties Of Glass-ceramics Synthesized From a Glass Frit. *SCI SINTER, 2(49)*, 139-147. https://doi.org/10.2298/sos1702139c.

Dembele, S., Rosario, R.A.F., & Wen, J.X., . (2012). Thermal breakage of window glass in room fires conditions – Analysis of some important parameters. *Building and Environment, 54*, 61-70. https://doi.org/10.1016/j.buildenv.2012.01.009.

Deng, L., Miyatani, K., Suehara, M., Amma, S., Ono, M., Urata, S., & Du, J. (2021). Ion-exchange Mechanisms and Interfacial Reaction Kinetics During Aqueous Corrosion Of Sodium Silicate Glasses. *npj Materials Degradation, 1(5).* , 00159-4. https://doi.org/10.1038/s41529-021-00159-4.

Du, Q., Sun, Q., Ding, H., Zhang, G., Fan, Y., & An, F. (2022). Experimental Study On Bulk Modulus and Dissipation Of Dry And Wet Granular Samples Under Vertical Vibration. *Acta Phys. Sin., 18(71)*, 184501. https://doi.org/10.7498/aps.71.20220329.

Eeu, T. Y., Leong, P. M., Pang, X. G., Ibrahim, Z., & Hussin, R. (2013). Structural Study Of Cadmium Lead Borophosphate Glass. *AIP Conference Proceedings, 1528(1)*, 296-299. https://doi.org/10.1063/1.4803612.

Elkhoshkhany, N., Marzouk, S. Y., El-Sherbiny, M., Ibrahim, H., Burtan, B., Alqahtani, M. S.,& Yousef, E. S. . (2022). Investigation Of Structural, Physical, and Attenuation Parameters Of Glass: Teo2-bi2o3-b2o3-tio2-re2o3(Re: La, Ce, Sm, Er, And Yb), And Applications Thereof. *Materials, 15(15)*, 5393. https://doi.org/10.3390/ma15155393.

Everson, K., Anajembe, K. C., & Baljinder, K. K. (2011). The effect of fire-retardant additives and a surface insulative fabric on fire performance and mechanical property retention of polyester composites. *Fire and Materials, 35(3)*, 143-155. https://doi.org/10.1002/fam.1039.

Gao, P., Jin, C., Jin, C., Chen, B., Chen, B., Yang, Z., & Zhao, D. (2021). Effect Of Gd2o3 Addition On the Microstructure And Properties Of Gd2o3-yb2o3-y2o3-zro2 (Gyyzo) Ceramics. *Materials, 23(14)*, 7470. https://doi.org/10.3390/ma14237470.

Geoffroy, L., Samyn, F., Jimenez, M., & Bourbigot, S. (2018). Intumescent Polymer Metal Laminates for Fire Protection. *Polymers, 10(9)*, 995. https://doi.org/10.3390/polym10090995.

Gharbi, A., Feki, H. E., & Oudadesse, H. (2016). Novel Alkali Borosilicate Glasses: Preparation, Structural Investigation and Thermal Study. *Korean J. Chem. Eng., 4(33*, 1456-1461. https://doi.org/10.1007/s11814-015-0287-4.

Gin, S., Collin, M., Jollivet, P., Fournier, M., Minet, Y., Dupuy, L.,& Du, J. . (2018). Dynamics Of Self-reorganization Explains Passivation Of Silicate Glasses. *Nature Communications, 1(9)*, 2619. https://doi.org/10.1038/s41467-018-04511-2.

Gravit, M., Klimin, N., Dmitriev, I., Karimova, A., & Fedotova, E. (2019). Fire technical properties of intumescent and ablative fire resistant glass. *IOP Conference Series: Materials Science and Engineering, Volume 666, Quality Management and Reliability of Technical Systems 20–21* (pp. 012095. DOI 10.1088/1757-899X/666/1/012095). IOP Science.

Grigoriadis, K. (2015). Material Fusion: a Research Into The Simulated Blending Of Materials Using Particle Systems. *International Journal of Architectural Computing, 3-4(13)*, 335-352. https://doi.org/10.1260/1478-0771.13.3-4.335.

Hamzah, S. A., Saeed, M. A., Wagiran, H., Hashim, I. H. (2017). Thermoluminescence (Tl) Dosimeter Of Dysprosium Doped Strontium Borate Glass For Different Glass Modifiers (Na, Li, Ca) Subjected From 1 To 9 Gy Doses. *EPJ Web Conf., (156)*, 00007. https://doi.org/10.1051/epjconf/201715600007.

Han. X. (2015). Investigation on the complex interaction between particle and substrate in mechanical polishing of silica glass. *The International Journal of Advanced Manufacturing Technology, 85*, 2567–2575. https://doi.org/10.1007/s00170-015-8017-y.

Hassan, M. K., Hasnat, M. R., Loh, K. P., Hossain, M. D., Rahnamayiezekavat, P., Douglas, G., & Saha, S. (2023). Effect of Interlayer Materials on Fire Performance of Laminated Glass Used in High-Rise Building: Cone Calorimeter Testing. *Fire, 6(3)*, 84. https://doi.org/10.3390/fire6030084.

Hu, W., Nurcholik, S. D., Lee, S. K., & Lin, T. H. (2016). Evaluations On Heat Resistance Of Curtains With Water Film In a Fire. *Journal of the Chinese Institute of Engineers, 5(39)*, 615-622. https://doi.org/10.1080/02533839.2016.1146092.

Jiang, S., Zhu, L., Liu, S., Yang, Z., Lan, S., & Wang, Y. (2022). Densification and Heterogeneity Enhancement Of Fe-based Metallic Glass Under Local Plastic Flow. *Acta Physica Sinica, 5(71)*, 058101. https://doi.org/10.7498/aps.71.20211304.

Kiminami, C. S., Koga, G. Y., Bolfarini, C., & Botta, W. J. (2023). Development Of Fe-based Glass Former Alloys For Thermal Spray Coatings With Optimized Corrosion and Wear Properties. *ARTIGO ORIGINAL – EDIÇÃO ESPECIAL 75TH ABM ANNUAL CONGRESS*, (pp. e2769. https://doi.org/10.4322/2176-1523.20222769).

Kotz, F., Arnold, K., Bauer, W., Schild, D., Keller, N., Sachsenheimer, K., Nargang, T. M., Richter, Ch., Helmer, D. & Rapp, B. E. . (2017). Three-dimensional printing of transparent fused silica glass. *Nature, 544*, 337-339. https://doi.org/10.1038/nature22061.

Kugatov, P. V., Raznoushkin, A. E., Zhirnov, B. S., Eremenko, A. E., & Dryndina, D. S. (2020). Kugatov, P. V., Raznoushkin, A. E., Zhirnov, B. S., Eremenko, A. E., Dryndina, D. S. *Coke and Chemistry volume, 2(63)*, 81-83. https://doi.org/10.3103/s1068364x20020040.

Kumar, S.A., & Nagaraja, B.K. (2021). Thermal stability and flammability characteristics of phenolic syntactic foam core sandwich composites. *Journal of Sandwich Structures & Materials, 23(7)*, 3234-3249. doi:10.1177/1099636220926661.

Lemrich, L., Carmeliet, J., Johnson, P., Guyer, R. A.,& Jia, X. . (2017). Dynamic Induced Softening In Frictional Granular Materials Investigated By Discrete-element-method Simulation. *Physical Review E, 6(96)*, 062901. https://doi.org/10.1103/physreve.96.062901.

Li, L., Jiachen, F., Yuanting, Y., & Wenke, Q. (2019). The Scientific Layouts of Glass Bridges in Tourist Areas from the Perspective of Sustainable Development. *Proceedings of the 1st International Symposium on Economic Development and Management Innovation (EDMI 2019)* (pp. NA. https://doi.org/10.2991/edmi-19.2019.55). Springer Nature.

Lin, Z., Zhao, X., Wang, C., Dong, Q., Qian, J., Zhang, G., & Hu, L. (2022). Rapid Pressureless Sintering Of Glasses. *Small, 17(18)*, 2107951. https://doi.org/10.1002/smll.202107951.

Lu, Y., Zhang, Z., Lu, X., Qin, Z., Shen, J., Huang, Y., & Liaw, P. K. (2017). Cooling-rate Induced Softening In a Colloidal Glass. *Scientific Reports, 1(7)*, 16882. https://doi.org/10.1038/s41598-017-17271-8.

Maria, K., Alexander, R., Ingo, K., & Thomas, S. (2016). Tunable Aryl Alkyl Ionic Liquids with Weakly Coordinating Tetrakis((1,1,1,3,3,3-hexafluoropropan-2-yl)oxy)borate [B(hfip)4] Anions. *Chemistry A European Journal, 22(29)*, 10044-10049. https://doi.org/10.1002/chem.201601063.

Martins, M.S.S., Schartel, B., Magalhaes, D., & Pereira. C.M.C. (2017). The effect of traditional flame retardants, nanoclays and carbon nanotubes in the fire performance of epoxy resin composites. *Fire and Material, 41(2)*, 111-130. https://doi.org/10.1002/fam.2370.

McLaren, C. T., Heffner, W. R., Raj, R., & Jain, H. (2017). Electric Field- induced Softening Of Alkali Silicate Glasses. *Jounal of American Ceramic Society, 6(101)*, 2277-2286. https://doi.org/10.1111/jace.15387.

Müller, H., Strubel, C., & Bange, K. (2006). Characterization and Identification Of Local Defects In Glass. *Scanning, 1(23)*, 14-23. https://doi.org/10.1002/sca.4950230103.

Nanba, T., Benino, Y., & Akai, T. (2022). Environmental Activities On Glass In Japan. *Journal of the Ceramic Society of Japan, 8(130)*, 605-610. https://doi.org/10.2109/jcersj2.22052.

Ngoc, N.N., Vinh, T.L., Thanh, X.L., & Soung, T. H. . (2020). Synthesis and Characterization of New Eco-Friendly Fire-Retardants Based on Soda-Silicate Glass. *Asean Journal of Chemical Engineering, 20(2)*, 120-129. https://doi.org/10.22146/ajche.53954.

Ni, Z., Lu, S., & Peng, L. (2012). Experimental study on fire performance of double-skin glass facades. *Journal of Fire Sciences, 30(5)*, 457-472. https://doi.org/10.1177/073490411244717.

Podawca, K., & Przywózki, M. (2019). The Impact Of Structural and Material Solutions For Glazing Connections On Deformation During Fire. *Safety & Fire Technology, 1(53)*, 118-128. https://doi.org/10.12845/sft.53.1.2019.7.

Rochmat, F.K., Annisa, A. & Lusi, S. (2022). Preparation of TiO2/ZrO2 Composite as Photoanode of Ruthenium-Based Dye-Sensitized Solar Cells. *Journal of Physics: Conference Series, 2376*, 012007 DOI 10.1088/1742-6596/2376/1/012007.

Ruengsri, S. (2014). Radiation Shielding Properties Comparison Of Pb-based Silicate, Borate, and Phosphate Glass Matrices. *Science and Technology of Nuclear Installations*, 1-5. https://doi.org/10.1155/2014/218041.

Sikora, P., Horszczaruk, E., & Rucińska, T. (2015). The Effect Of Nanosilica and Titanium Dioxide On The Mechanical And Self-cleaning Properties Of Waste-glass Cement Mortar. *Procedia Engineering, (108)*, (pp. 146-153. https://doi.org/10.1016/j.proeng.2015.06.130).

Silvestri, A., Fiorentino, S., & Vandini, M. (2023). Once Upon a Glass—cycles, Recycles And Reuses Of A Never-ending Material. Heritage, 1(6), 662-671. *Heritage, 1(6)*, 662-671. https://doi.org/10.3390/heritage6010035.

Smedskjær, M. M., Mauro, J. C., Youngman, R. E., Hogue, C. L., Potuzak, M., & Yue, Y. (2011). Topological Principles Of Borosilicate Glass Chemistry. *Journal of Physics and Chemistry, 44(115)*, 12930-12946. https://doi.org/10.1021/jp208796b.

Smirniou, M., & Rehren, T. (2010). Direct Evidence of Primary Glass Production in Late Broze Age Amarna, Egypt. *Annali di Chimica, 96(9-10),* 58-80. https://doi.org/10.1111/j.1475-4754.2010.00521.x.

Sørensen, S. S., Johra, H., Mauro, J. C., Bauchy, M., & Smedskjær, M. M. (2019). Boron Anomaly In the Thermal Conductivity Of Lithium Borate Glasses. *Physical Review Materials, 3 (7)*, 075601. https://doi.org/10.1103/physrevmaterials.3.075601.

Sun, J., Lin, Z., Xu, B., & Rong, J. (2015). Effect Of Glass Fibers On the Mechanical And Thermal Conductivity Properties Of Pp/alumina Composites. *Proceedings of the 2015 International Conference on Mechatronics, Electronic, Industrial and Control Engineering* (pp. 291-295. https://doi.org/10.2991/meic-15.2015.69). Atlantis Press.

Swan, C. M., Rehren, T., Dussubieux, L., & Eger, A. A. (2017). High-boron and High-alumina Middle Byzantine (10th-12th Centuryce) Glass Bracelets: A Western Anatolian Glass Industry. *Archaeometry, 2(60)*, 207-232. https://doi.org/10.1111/arcm.12314.

Telli, M. (2016). Soda Lime Silicate Glass-copper Metal Joining By Controlled Heat Treatments In Air. *5th International Science Congress & Exhibition APMAS2015,*, (pp. 482-484. https://doi.org/10.12693/aphyspola.129.482).

Thieme, C., Schlesier, M., Dike, E. O., Rüssel, C. (2017). Variable Thermal Expansion Of Glass-ceramics Containing Ba1−xSrxZn2Si2O7. *Scientific Reports volume, 7*, 3344. https://doi.org/10.1038/s41598-017-03132-x.

Tongtong, Z., & Di, Co. (2021). Simulation Study on the Influence of Fire Partition on Curtain Wall Temperature in Super High-Rise Buildings in China. *Complexity*, 4124049. https://doi.org/10.1155/2021/4124049.

Tyszkiewicz, C. (2018). Single mode condition for shallow silica–titania rib waveguides. *Optical and Quantum Electronics*, *50*, 360. https://doi.org/10.1007/s11082-018-1627-5.

Vakhula, Y., Lutsyuk, I., Melnyk, Y., & Narok, O. (2018). Effect Of Low-melting Glass On Thermal and Physical Properties Of Polymer Composites. *ChChT, 4(12)*, 488-491. https://doi.org/10.23939/chcht12.04.488.

Yaowakulpattana, P., Wakasugi, T., Kondo, S., & Kadono, K. (2015). Effect Of Alkaline and Alkaline-earth Metal Oxides Addition On The Glass Formation And Crystallization Of Zno-al2o3-sio2 Glasses. *Engineering Journal, 3(19)*, 21-34. https://doi.org/10.4186/ej.2015.19.3.21.

Ye, M., & Shi, B. (2018). Zirconia Nanoparticles-induced Toxic Effects In Osteoblast-like 3t3-e1 Cells. *Nanoscale Research Letters volume 13*, 353. https://doi.org/10.1186/s11671-018-2747-3.

Zhang, L., Wang, Y., & Zhang, Z. . (2022). Nanoparticles in Glass_ Influence on Thermal Expansion and Other Properties. *Journal of The European Ceramic Society*, *41(1)*, 324-335.