Review of Durability Parameters for Basalt Fiber Concrete in Structural Applications

Abhijeet A. Ulagadde *[1], Dr.Atul Bhatore[2]

[1] *SAGE University, Department of Civil Engineering Department, PhD. Scholar, India,*

[2] *SAGE University, Department of Civil Engineering Department, Associate Professor, India,*

Abstract:

This literature review synthesizes existing research on the durability of basalt fiber concrete, examining its performance under various environmental stressors and exploring the underlying mechanisms governing its longevity. Basalt fiber in structural concrete offers a compelling alternative to traditional materials across various applications, delivering exceptional performance at a competitive cost. They strike a balance between mechanical and physical properties, while also exhibiting significant chemical resistance to corrosive substances and fluids typically found in harsh environments. The effects of basalt fiber and dosage are discussed in detail in term of chemical, mechanical and durability properties of basalt fiber, followed by highlighting some areas for future research. As a reinforcing material, basalt fibers are gaining attention and emerging as a viable alternative to traditional fibers like glass and carbon. It would be concluded that basalt fiber can potentially replace the other conventional fibers in structural concrete which are being used in the industry.

Keyword: Basalt Fiber, Durability, Sustainable Construction

1. Introduction:

Basalt fibers are manufactured by melting basalt rocks, which are naturally occurring igneous rocks, and then converting the molten material into fibers. The production process leverages natural energy sources to minimize environmental impact. Three types of basalt fibers are produced and utilized: (a) Basalt Continuous Fibers: used for reinforcing materials, composite products, fabrics, and non-woven materials. (b) Basalt Staple Fibers: used for thermal insulation materials. (c) Basalt Superthin Fibers: used for high-quality heat and sound insulation, as well as fireproof materials. Basalt fiber is a high-tech, eco-friendly material that offers numerous benefits without environmental pollution. Its applications span military and civilian fields, holding significant theoretical and strategic importance. As a natural, 100% basalt-based material, basalt fiber offers several eco-friendly benefits: Non-toxic and hazardous substance-free, Recyclable, Carbon-neutral production process, furnace-friendly during incineration. Overall, basalt fiber is an environmentally responsible material ideal for sustainable construction and insulation applications. The production of basalt fibers has a long history, dating back to 1923 when Paul Dhe was awarded U.S. patent 1,462,446 in the United States. In 1995, the use of basalt fibers expanded into a wider range of civilian applications [1]. Basalt fibers have emerged as a promising material for the fiber-reinforced polymer composite industry due to their exceptional properties [2]. Derived from basalt, the most abundant rock in the Earth's crust and a primary component of the ocean floor [3], these fibers have diameters ranging from 9 to 13 μm. Their chemical composition varies depending on the specific basaltic rock and manufacturing process used [4]. The chemical composition of basalt fibers, primarily consisting of silicon, aluminum, calcium, magnesium, iron, and other elemental oxides, is influenced by the producer and the proportions of different basaltic rocks used. These unique fibers have found widespread applications in various industries, including the production of high-performance concrete aggregates, rock wool, and chemical-resistant artifacts [5]. Basalt fiber is a preferred reinforcement in fiber-reinforced polymers due to its exceptional properties, derived from a unique raw material fusion process. These advantages make basalt fiber-reinforced polymers an attractive alternative to glass fiber-reinforced polymers and carbon fiber-reinforced polymers offering comparable stiffness and expense, along with enhanced corrosion and fire resistance [6-11]. The advantages of fiber-reinforced polymers for civil engineering applications such as structural forms, bridge decks, internal reinforcements, and externally bonded reinforcements [12]. The incorporation of fibers has led to the development of various advanced cementitious materials, including fiber-reinforced concrete, engineering cementitious composites, strain-hardening cement-based composites, high-performance fiber-reinforced cementitious composites, and ultra-high toughness cementations composites [13-14]. However, steel fibers can compromise the durability of concrete due to their susceptibility to corrosion [15], and increase the self-weight of concrete elements. Alternative fiber options have their own limitations. This reviews aims to integrate existing research on the processing parameters of basalt fiber-reinforced concrete, comparing various approaches to identify optimal parameters that achieve outstanding durability performance and practical applications. Additionally, it explores the use of fiber-reinforced polymers in civil infrastructure. The study's ultimate goal is to identify knowledge gaps and inform future research directions, advancing the development of innovative and sustainable construction materials.

2. Application of Basalt Fiber in Civil Structures:

Basalt fibers are increasingly used in construction, particularly in civil structures, due to their exceptional properties: (i) Low heat transfer rate, making them fire-resistant (ii) High tensile strength and low thermal conductivity, ideal for bridges and railway sleepers (iii) Non-corrosive, high specific strength, hardness, and low weight, suitable for tunnel construction, especially near water (iv) The use of basalt fiber-reinforced concrete in road construction enhances safety and ride quality.

3. Properties of Basalt fiber:

Basalt fiber is one of the earth's strongest natural fibers, boasting all the properties. Its unique combination of rigidity, lightness, and high strength-to-weight ratio makes it an ideal material for various applications, with the added benefit of being biodegradable as shown in Fig.1.

Figure 1: Chopped basalt fiber 12 mm and 24 mm

3.1. Mechanical Properties of Basalt fiber:

The mechanical properties of the basalt fiber reported in different studies along with expected ranges are summarized in Table 1 [16-20]. The modulus of elasticity ranges from 88 to 115 GPa, while tensile strength varies from 2630 to 4500 MPa. These property variations can be attributed to factors such as manufacturing process, chemical composition, and compatibility with the basalt matrix [21-22].

Table 1: Mechanical Properties of Basalt Fiber

Ref.	Density (g/cm^3)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation at break (%)	Diameter (µm)
Nassani [16]	2.8	4100-4800	89	3.15	13-20
Kizilkanat et.al. [17]	2.8	4100-4800	89	3.15	13-20

Hu et.al. [18]	2.65	2630	88.9	2.99	16
Ayub et.al. [19]	--	4100-4840	93.1-110	3.10	18
Zhou et.al. [20]	2.65	3500-4500	95-115	2.4-3.0	15
Jiang et.al.[26]	2.65	4100-4800	93-110	3.1-3.2	20

3.2. Chemical Properties of Basalt fiber:

The chemical composition of basalt fibers significantly influences their mechanical properties shown in Table 2. Research shows that higher percentages of SiO_2, MgO, and Al_2O_3 compounds correlate with increased tensile strength and modulus of elasticity [21]. Specifically, studies found that: Tensile strength increases with SiO_2 content between 49% and 57% [22]. Higher SiO_2 and Al_2O_3 content improve thermal properties [23]. The presence of approximately 12% iron oxide gives basalt fiber its characteristic brown color. These findings highlight the importance of chemical composition in determining the properties of basalt fibers.

Table 2: Chemical Properties of Basalt Fiber:

Ref.	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Fe_2O+FeO (%)	Na_2O+K_2O (%)	TiO_2 (%)	R_2O (%)	Li_2O (%)
Ayub et.al. [19]	51.6-89.3	14.6-18.3	5.9-9.4	3-5.3	9-14	08-2.25	0.8-2.25	--	--
Ding et.al.[21]	53.83	15.31	6.62	4.73	8.12	3.60	0.91	--	--
Jamshaid, and Mishra [24]	52.8	17.5	8.59	4.96	10.3	4.8	1.38	--	--
Afroz [25]	48-60	17.5	5-9	3-6	9.-14	3-6	0.6-2.5	4-5	0.1-0.3

4. Durability Properties of Basalt Fiber Concrete:

In this section various properties of basalt fiber concrete are reviewed from literature.

4.1 Pore Size Distribution and Porosity:

According to Wu and Lian [27], pores in cement-based materials can be categorized into four types based on their size: (0–20 nm) harmless, (20–100 nm) minor harmful, (100–200 nm) harmful, and (>200 nm) very harmful. The test results [26] showed significant changes in pore size distribution for concrete reinforced with 22 mm long basalt fibers at 0.3 vol% dosage, compared to plain concrete, after 28 days of curing: Harmless pores increased by 7%, Minor harmful pores decreased by 10%, Harmful pores increased by 1%, Very harmful pores increased by 3%. Overall, the total volume of pores in basalt fibers concrete increased by 11.8%, and total porosity rose by 7.9% compared to plain concrete, finally this study indicates that the paste containing basalt fiber presents a higher porosity. Research by Guo et al. [28] revealed that increasing the basalt fiber dosage leads to higher porosity, specifically: A 0.3 vol% basalt fiber dose resulted in a 12% increase in porosity compared to control specimens. Doubling the dose to 0.6 vol% led to a significant 39.1% increase in porosity. Bright Singh and Madasamy [29] incorporated basalt fibers into pervious concrete and observed a marginal decrease in porosity. This contrasts with the increase in porosity seen when basalt fiber is added to normal concrete. The decrease in porosity in pervious concrete, which inherently has a porosity of 15-25%, may be attributed to the fibers clogging some pores.

4.2 Water Absorption, Penetration and Chloride Diffusion:

A linear correlation between basalt fiber dosage and water absorption in basalt fiber reinforced concrete. Specifically, water absorption increased by approximately 13% at a 0.1 vol% basalt fiber content and by 33% at a 0.5 vol% basalt fiber content [30]. Incorporating basalt fibers reduced chloride permeability, although no distinct correlation was observed between chloride permeability and fiber length or dosage. Although basalt fiber-reinforced concrete showed reduced chloride permeability, it exhibited the highest water penetration depth among the studied specimens. Given the conflicting findings on chloride ingress in basalt fiber reinforced concrete, further research is necessary to fully understand these properties [31]. The water absorption test is a key indicator of concrete durability, measuring its resistance to water penetration. Incorporating of basalt fibers at dosages of 0.07 and 0.14 vol. % resulted in modest increases in water absorption, by 3% and 4%, respectively [32]. Chloride ion permeability measures the susceptibility of concrete to chloride ion infiltration from the surrounding environment, posing a corrosion risk to steel reinforcement. Chloride ions can penetrate concrete through various mechanisms, including water diffusion, capillary absorption, and impregnation [33]. The incorporation of basalt fibers into concrete increases the charge passing through the concrete, compared to plain concrete [34]. The increased charge passing through the concrete can be attributed to the higher porosity and water absorption, as previously discussed. Greater porosity facilitates more water ingress, leading to higher charge passing. Nevertheless, despite this increase, these mixtures still meet the ASTM standard criteria for low chloride permeability [35]. The chloride diffusion coefficient represents the rate at which chloride ions are transferred across a unit area. As a crucial parameter in concrete, it helps predict the service life of structures by assessing the primary cause of steel reinforcement corrosion: chloride ion ingress [34].

4.3. Temperature effect and Plastic shrinkage:

Research has demonstrated the potential of basalt fiber-reinforced concrete to withstand high temperatures, with studies showing its suitability for use within a temperature range of 200°C to 800°C [36]. The investigation concluded that the effects of basalt fibers on hybrid fiber-reinforced concrete exposed to 850°C. The results showed that increasing basalt fibers length and content led to higher mass loss and strength reduction, likely due to increased porosity. Nonetheless, fiber-reinforced specimens outperformed control specimens in compressive strength, strain, and toughness [37]. The experimental study showed that the impact of elevated temperatures (300°C and 600°C) on concrete specimens containing 0.5% basalt fibers and compared them to fiber-free controls. Notably, the basalt fiber reinforced concrete specimens exhibited numerous small cracks, whereas the control specimens displayed wider cracks. Moreover, no spalling was observed in the fiber-reinforced specimens, attributed to the bridging action of the fibers, which prevented concrete spalling under high-temperature exposure. The authors further reported that incorporating basalt fibers resulted in higher residual mechanical properties (compressive, splitting tensile and flexural strengths) in concrete after exposure to elevated temperatures [38]. Plastic shrinkage occurs in freshly placed concrete, characterized by volumetric contraction due to water evaporation from the surface before hardening. Additionally, autogenously shrinkage resulting from cement hydration reduces internal moisture, potentially leading to plastic shrinkage cracking if evaporation exceeds bleeding water rising to the surface. When restrained, shrinkage induces tensile stresses, and if these stresses surpass the concrete's tensile strength, cracking occurs. The incorporation of basalt fibers into concrete effectively reduced the strain caused by shrinkage in fresh concrete [39-41].

4.4. Freeze-Thaw Resistance of Basalt Fibers Concrete:

The freeze-thaw resistance of concrete is crucial in cold climates. Studies [42-43] have consistently shown that adding basalt fibers to concrete significantly enhances its durability in freeze-thaw cycles. This improvement is attributed to the fibers' ability to bridge cracks, restrain crack propagation, and minimize water ingress, thereby reducing damage from ice expansion. However, the magnitude of this improvement depends on various factors, including: Fiber content and length, Severity of freeze-thaw cycles, Incorporation of supplementary cementations materials like fly ash etc. Optimizing fiber content and mix design requires careful consideration of these interacting factors to maximize freeze-thaw resistance.

4.5. Sulfate Attack Resistance:

Sulfate attack can significantly deteriorate concrete structures exposed to sulfate-rich environments. Research on the sulfate resistance of basalt fiber-reinforced concrete is limited, but available studies suggest that basalt fibers may enhance sulfate resistance. The mechanisms behind this improvement are not fully understood, but are likely related to: reduced porosity and improved crack control. A denser concrete matrix with fewer pores reduces the surface area for sulfate ion attack, delaying degradation. Basalt fibers also bridge and restrain cracks, limiting sulfate ion penetration and chemical reaction [44-45].

4.6. Resistance of Alkali-Aggregate Reaction:

The alkali-aggregate reaction can cause significant expansion and cracking in concrete, particularly with reactive aggregates and high-alkali cement. Despite extensive research on basalt fiber concrete mechanical and durability properties, its resistance to alkali-aggregate reaction remains understudied [46-47].

4.7. Other Durability Aspects:

Several additional durability characteristics of basalt fiber-reinforced concrete require further investigation, including**:**

4.7.1. Carbonation Resistance:

Carbonation, a reaction between carbon dioxide and calcium hydroxide in the cement matrix, can lower concrete pH and potentially corrode reinforcing steel. Research on basalt fibers' impact on carbonation is scarce. [48] Further investigation is necessary to determine how basalt fiber content and mix design affect carbonation depth and rate.

4.7.2. Abrasion Resistance:

Concrete surfaces like pavements and floors require high abrasion resistance to withstand wear. Basalt fibers, due to their high tensile strength and stiffness, show promise in enhancing concrete's abrasion resistance [49-50]. Further research is necessary to quantify this benefit and optimize mix designs for optimal abrasion resistance.

4.7.3. Long-Term Performance:

Extensive research is needed to assess the long-term durability and service life of basalt fiber-reinforced concrete under various environmental conditions. Long-term exposure studies that simulate real-world service conditions are crucial for evaluating BFRC's performance over time and accurately predicting its service life. These studies should track changes in material properties over extended periods, considering the combined effects of multiple environmental factors [51-52].The precise balance of basalt fiber is crucial for producing robust, crack-resistant concrete. This is particularly vital for large-scale infrastructure projects, such as dams and bridges, as well as for precast concrete components [53]. Basalt fibers exhibit exceptional thermal resilience, maintaining integrity up to 1,000°C without substantial deterioration. Additionally, their inherent chemical and environmental resistance properties contribute to their enhanced durability and longevity [54]. The construction industry is grappling with substantial environmental challenges [55], but the emergence of basalt concrete presents a promising solution. To fully harness their potential, further research is necessary to optimize the integration of basalt fiber in structural concrete production. Additionally, a deeper understanding of their properties and behavior is crucial to unlock the benefits of basalt fiber concrete and mitigate the industry's environmental footprint.

5. Conclusions and Future Research:

1. This study suggests that basalt fibers are preferred in structural concrete because of heavy-duty, lightweight applications in the civil industry.
2. Basalt rock serves as a viable alternative raw material for fiber production, owing to its favorable chemical composition, widespread availability, low impurity levels, and excellent fiber-forming capabilities in its molten state.

3. The environmentally friendly and non-hazardous nature of basalt fibers, combined with their excellent mechanical, chemical, and thermal properties, make them an innovative material for various applications, including construction, energy efficiency, automotive, aeronautics, and industrial sectors.

4. A comprehensive cost-benefit analysis comparing the economic viability of basalt fiber-reinforced concrete with traditional concrete and other fiber-reinforced concretes is crucial for promoting its adoption in construction projects.

5. Further research is needed to understand basalt fibers concrete long-term durability and develop predictive models. Addressing knowledge gaps will optimize basalt fibers concrete design and promote sustainable infrastructure development, driving innovation in eco-friendly construction materials.

References

[1] "Basalt fiber". basfiber.com (in Russian, English, German, Korean, and Japanese). Retrieved 2018-06-21.

[2] Soares, B., Preto, R., Sousa, L., & Reis, L. (2016). Mechanical behavior of basalt fibers in a basalt-UP composite. Procedia Struct. Integr. 1, .82–89, https://doi.org/ 10.1016/j.prostr.2016.02.012.

[3] Jamshaid, H., Militký, J., Mishra, R., & Koukolikova, L. (2027). Basalt fibers and their composites in: Novelties in Fibrous Material Science. 2–61.

[4] De Fazio, P. (2011). Basalt Fibra: from Earth and Ancient Material for Innovative and Modern Application, Ambiente e Innovazione, Energia.

[5] Jamshaid, H., Mishra, R. (2015). A green material from rock: basalt fiber – a review. J. Text. Inst. 107 (7),923–937. https://doi.org/10.1080/ 00405000.2015.1071940

[6] Wu, G., Wang, X., Wu, Z., Dong, Z, & Zhang, G. (2014). Durability of basalt fibers and composites in corrosive environments. J. Compos. Mater. 49 (7), 873–887. https://doi.org/10.1177/0021998314526628.

[7] Lu, Z., Tan, S., Huang, P., Lei, Z., Liu, F., & Xie, J. (2020) Durability of cement mortar-covered BFRP bars in simulated seawater environment, Construct. Build. Mater. 234, 117803, https://doi.org/10.1016/j.conbuildmat.2019.117803.

[8] Lu, Z., Su, L., Tan, S., Li, Y., Xie, J., & Liu, F. (2020). Long-term shear performance of bare and cement mortar-coated BFRP bars in corrosive environments, Construct. Build. Mater. 237, 117658, https://doi.org/10.1016/j. conbuildmat.2019.117658.

[9] Lu, Z., Su, L., Xian, G., Lu, B., & Xie, J. (2020) Durability study of concrete-covered basalt fiber-reinforced polymer (BFRP) bars in marine environment, Compos. Struct. 234, 111650, https://doi.org/10.1016/j.compstruct.2019.111650.

[10] Sim, J., Park, C., & Moon, D.Y. (2005). Characteristics of basalt fiber as a strengthening material for concrete structures, Compos. B Eng. 36 (6–7), 504–512, https://doi.org/10.1016/j.compositesb.2005.02.002.

[11] Lu, Z., & Xian, G. (2016). Resistance of basalt fibers to elevated temperatures and water or alkaline solution immersion. Polym. Compos. 39, 2385–2393.

[12] Bakis, C.E. (2002). Fiber-reinforced polymer composites for construction - state-of-the-art review. J. Compos. Construct. 6 (2), 73–87, https://doi.org/ 10.1061/(ASCE)1090-0268(2002)6:2(73)

[13] Huang, T., & Zhang, Y.X. (2022). Multiscale modeling of multiple-cracking fracture behavior of engineered cementitious composite (ECC). Adv. Eng. Cem. Compos. Mater. Struct. Numer. Model. 337–388. https://doi.org/10.1016/B978-0-323-85149-7.00003-3

[14] Hou, L., Wang, J., Huang, T., Shen, C., Aslani, F., & Chen, D. (2019). Flexural behaviour of corroded reinforced concrete beams repaired with ultra-high toughness cementitious composite. Construct. Build. Mater. 211, 1127–1137. https://doi.org/10.1016/j. conbuildmat.2019.03.214

[15] Hou, L., Xu, R., Zang, Y., Ouyang, F., Chen, D. & Zhong, L. (2020). Bond behavior between reinforcement and ultra-high toughness cementitious composite in flexural members. Eng. Struct. 210, 110357 https://doi.org/10.1016/j. engstruct.2020.110357

[16] Nassani, D.E. (2020). Experimental and analytical study of the mechanical and flexural behavior of hybrid fiber concretes. Structures 28, 1746–1755. https://doi.org/ 10.1016/j.istruc.2020.10.014

[17] Kizilkanat, A.B., Kabay, N., Akyüncü, V., Chowdhury, S. & Akça, A.H. (2015). Mechanical properties and fracture behavior of basalt and glass fiber reinforced concrete: an experimental study. Construct. Build. Mater. 100, 218–224. https://doi.org/ 10.1016/j.conbuildmat.2015.10.006

[18] Hu, X., Guo, Y., Lv, J. & Mao, J. (2019). The mechanical properties and chloride resistance of concrete reinforced with hybrid polypropylene and basalt fibres. Materials (Basel) 12. https://doi.org/10.3390/ma12152371

[19] Ayub, T., Shafiq, N. & Khan, S.U. (2016). Compressive stress-strain behavior of HSFRC reinforced with basalt fibers. J. Mater. Civ. Eng. 28, 1–11. https://doi.org/10.1061/ (asce)mt.1943-5533.0001441.

[20] Zhou, H., Jia, B., Huang, H., Mou, Y., 2020. Experimental study on basic mechanical properties of basalt fiber reinforced concrete. Materials (Basel) 13. https://doi.org/ 10.3390/ma13061362.

[21] Ding, L., Liu, Y., Liu, J. & Wang, X. (2019). Correlation analysis of tensile strength and chemical composition of basalt fiber roving. Polym. Compos. 40, 2959–2966. https://doi.org/10.1002/pc.25138.

[22] Chen, X., Zhang, Y., Huo, H. & Wu, Z. (2020). Study of high tensile strength of natural continuous basalt fibers. J. Nat. Fibers 17, 214–222. https://doi.org/10.1080/ 15440478.2018.1477087.

[23] Liu, J., Yang, J., Chen, M., Lei, L. & Wu, Z. (2018). Effect of SiO2, Al2O3 on heat resistance of basalt fiber. Thermochim. Acta 660, 56–60. https://doi.org/10.1016/j. tca.2017.12.023.

[24] Jamshaid, H. & Mishra, R. (2016). A green material from rock: basalt fiber – a review. J. Text. Inst. 107, 923–937. https://doi.org/10.1080/00405000.2015.1071940

[25] Afroz, M., Patnaikuni, I. & Venkatesan, S. (2017). Chemical durability and performance of modified basalt fiber in concrete medium. Construct. Build. Mater. 154, 191–203. https://doi.org/10.1016/j.conbuildmat.2017.07.153

[26] Jiang, C., Fan, K., Wu, F. & Chen, D. (2014). Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete. Mater. Des. 58, 187–193. https://doi.org/10.1016/j.matdes.2014.01.056

[27] Wu, Z.W, & Lian H.Z. (1999). High performance concrete. Beijing: Railway Press of China Beijing, 19–22.

[28] Guo, Y., Hu, X. & Lv, J. (2019). Experimental study on the resistance of basalt fibre-reinforced concrete to chloride penetration. Construct. Build. Mater. 223, 142–155. https://doi.org/10.1016/j.conbuildmat.2019.06.211

[29] Bright Singh, S., & Madasamy, M. (2022). Investigation of aggregate size effects on properties of basalt and carbon fibre-reinforced pervious concrete. Road Mater. Pavement Des. 23, 1305–1328. https://doi.org/10.1080/14680629.2021.1886158

[30] Saradar, A., Nemati, P., Paskiabi, A.S., Moein, M.M., Moez, H. & Vishki, E.H. (2020). Prediction of mechanical properties of lightweight basalt fiber reinforced concrete containing silica fume and fly ash: experimental and numerical assessment. J. Build. Eng. 32, 101732 https://doi.org/10.1016/j.jobe.2020.101732.

[31] Algin, Z. & Ozen, M. (2018). The properties of chopped basalt fibre reinforced self-compacting concrete. Construct. Build. Mater. 186, 678–685. https://doi.org/ 10.1016/j.conbuildmat.2018.07.089.

[32] Kabay, N. (2014). Abrasion resistance and fracture energy of concretes with basalt fiber. Construct. Build. Mater. 50, 95–101. https://doi.org/10.1016/j. conbuildmat.2013.09.040.

[33] Oh, B.H., Cha, S.W., Jang, B.S. & Jang, S.Y. (2002). Development of high-performance concrete having high resistance to chloride penetration. Nuclear Engineering and Design 212(1):221-231. DOI:10.1016/S0029-5493(01)00484-8

[34] Guo, Y., Hu, X. & Lv, J. (2019). Experimental study on the resistance of basalt fibre-reinforced concrete to chloride penetration. Construct. Build. Mater. 223, 142–155. https://doi.org/10.1016/j.conbuildmat.2019.06.211

[35] ASTM C1202, (2012). Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. Am. Soc. Test. Mater. 1–8. https://doi.org/10.1520/ C1202-17.2

[36] Adesina, A. (2021). Performance of cementitious composites reinforced with chopped basalt fibres – an overview. Construct. Build. Mater. 266, 120970 https://doi.org/ 10.1016/j.conbuildmat.2020.120970.

[37] Khan, M., Cao, M., Chaopeng, X. & Ali, M. (2022). Experimental and analytical study of hybrid fiber reinforced concrete prepared with basalt fiber under high temperature. Fire Mater. 46, 205–226. https://doi.org/10.1002/fam.2968

[38] Alaskar, A., Albidah, A., Alqarni, A.S., Alyousef, R. & Mohammadhosseini, H. (2021). Performance evaluation of high-strength concrete reinforced with basalt fibers exposed to elevated temperatures. J. Build. Eng. 35, 102108. https://doi.org/ 10.1016/j.jobe.2020.102108

[39] Dhir, R.K., de Brito, J., Silva, R.V. & Lye, C.Q. (2019). Deformation of Concrete Containing Recycled Concrete Aggregate. https://doi.org/10.1016/b978-0-08-100985-7.00009- 1

[40] Jianxia, S. (2012). Durability Design of Concrete Hydropower Structures. Comprehensive Renewable Energy, 377-403, https://doi.org/10.1016/B978-0-08-087872-0.00619-3

[41] Branston, J., Das, S., Kenno, S.Y. & Taylor, C. (2016). Influence of basalt fibres on free and restrained plastic shrinkage. Cem. Concr. Compos. 74, 182–190. https://doi.org/ 10.1016/j.cemconcomp.2016.10.004

[42] Li, W., Liu, H., Zhu, B., Lyu, X., Gao, X., & Liang, C. (2020). Mechanical Properties and Freeze–Thaw Durability of Basalt Fiber Reactive Powder Concrete. Applied Sciences, 10(16), 5682. https://doi.org/10.3390/app10165682

[43] Fan, X. C., Wu, D. & Chen, H. (2014). Experimental Research on the Freeze-Thaw Resistance of Basalt Fiber Reinforced Concrete. Advanced Materials Research, 919–921, 1912–1915. https://doi.org/10.4028/www.scientific.net/amr.919-921.1912

[44] Wang Z., Zhao K., Li Z., & Ma H. (2017). Experimental Study on Durability and Mechanical Properties of Basalt Fiber Reinforced Concrete under Sodium Sulfate Erosion. Chemical Engineering Transactions, 62, 961-966. https://doi.org/10.3303/CET1762161

[45] Zhang, Y.H., Zhong, W.L. & Fan, Lingling. (2024). Long-term durability investigation of basalt fiber-reinforced geopolymer concrete in marine environment. Journal of Materials Research and Technology, 31,593-605. https://doi.org/10.1016/j.jmrt.2024.06.078

[46] Al-kharabsheh, B., Arbili, Mohamed Moafak, Majdi, Ali, Alogla, S. M., Hakamy, A., Ahmad, J., & Deifalla, A. (2023). Basalt Fiber Reinforced Concrete: A Compressive Review on Durability Aspects. Materials. 16(1), 429, https://doi.org/10.3390/ma16010429

[47] Vatin, N. I., Hematibahar, M., & Gebre, T. (2024). Impact of basalt fiber reinforced concrete in protected buildings: a review. Frontiers in Built Environment. 10:1407327.

https://doi.org/10.3389/fbuil.2024.1407327

[48] Lu, Limin, Wang, Fei, Wu, Shaohua, Qin, Yuwen, Yuan, Guanglin, & Doh, JeungHwan. (2021). Experimental study on durability of basalt fiber concrete after elevated temperature. Wiley. https://doi.org/10.1002/suco.202000746

[49] Krayushkina, K., Khymeryk, T. & Bieliatynskyi, A. (2019). Basalt fiber concrete as a new construction material for roads and airfields. IOP Conf. Ser.: Mater. Sci. Eng. 708, 012088 https://doi.org/10.1088/1757-899X/708/1/012088

[50] Yu, Haiying, Meng, Tao, Zhao, Yuxi, Liao, Jianping, &Ying, Kanjun. (2022). Effects of basalt fiber powder on mechanical properties and microstructure of concrete. Case Studies in Construction Materials, 17, e01286, https://doi.org/10.1016/j.cscm.2022.e01286

[51] Taha, A. & Alnahhal, W. (2021). Bond durability and service life prediction of BFRP bars to steel FRC under aggressive environmental conditions. Composite Structures, 269, 114034.

https://doi.org/10.1016/j.compstruct.2021.114034

[52] Dong, Zhiqiang, Wu, Gang, Zhao, XiaoLing, & Lian, Jin-Long. (2018). Long-Term Bond Durability of Fiber-Reinforced Polymer Bars Embedded in Seawater Sea-Sand Concrete under Ocean Environments. American Society of Civil Engineers. https://doi.org/10.1061/(asce)cc.1943-5614.0000876

[53] Gohil, M., & Bansal, P. (2024). A Review on Experimental Study to Optimize Self-Curing Concrete by Using Light-Weight Aggregates. Tuijin Jishu/Journal of Propulsion Technology, 45 (3) 3480-3488.

[54] Prakash R. S., Sabarinathan C., Balaji C., Ganesh A., Raj Kumar M., Sai Kiruthic B. (2024). Experimental Investigation on Tribological and Thermal Characteristics of Basalt / Graphene Reinforced Pure Metallic Brake Pad Material. Tuijin Jishu/Journal of Propulsion Technology, 45(4), 571-579.

[55] Wagh, P.C., Solanki,H., Mistry, M., & Chowdhury., P. (2024). A Review of Alkali Activated Concrete Using Eco friendly Industrial Waste Materials. Tuijin Jishu/Journal of Propulsion Technology, 45 (4), 1545-1551.