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A Study on the Effect of Steel Fibres on the Properties of Concrete – A Review

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ABSTRACT:

Concrete's susceptibility to low tensile strength and limited strain capacity necessitate reinforcement for widespread construction use. Typically, continuous steel bars are strategically placed to withstand imposed tensile and shear stresses. In contrast, fibres-short, discontinuous, and randomly dispersed throughout concrete-yield a composite material known as fibre reinforced concrete. These fibres, made of steel, glass, polymer, or natural materials, more effectively control cracking due to their closely spaced distribution. However, it's crucial to note that fibres aren't a substitute for conventional steel bars; they serve distinct roles in advanced concrete technology, often complementing each other in various applications

Keywords: Steel fibre, Steel fibre reinforced concrete, Mechanical properties, Durability properties.

1. INTRODUCTION:

Among fibres, Steel Fibre (SF) stands out as the most prevalent for concrete reinforcement. Initially utilized to manage shrinkage in concrete, further exploration revealed its substantial impact: enhancing flexural toughness, energy absorption, ductility, reducing cracking, and improving durability (Altun et al., 2006). This paper delves into the effects of SF addition in concrete, exploring its mechanical properties and applications in Steel fibre Reinforced Concrete (SFRC). Steel fibres are small, discontinuous, and typically short filaments made from different types of steel. They're used as a reinforcement material in concrete to enhance its structural properties. These fibres are added to the concrete mix to improve its strength, durability, and resistance to cracking. The inclusion of steel fibres in concrete creates a composite material that can better withstand stresses like tension, bending, and shear forces. They help control cracking, especially in situations where traditional reinforcement like rebar might be difficult to implement or insufficient. Steel fibres can be straight or deformed, and their aspect ratio (length to diameter) can vary depending on the specific application requirements. The advantages of using steel fibres in concrete include increased toughness, impact resistance, and fatigue performance. They're often utilized in industrial flooring, tunnel linings, precast elements, and shotcrete applications. However, the effectiveness of steel fibres can depend on factors such as fibre type, dosage, concrete mix design, and the specific conditions of the project. Overall, steel fibres offer an additional method of reinforcing concrete structures, providing more flexibility and strength compared to traditional concrete mix. Steel fibres come in various types, each designed to suit specific applications and project requirements. Some common types of steel fibres include:

1.Straight Steel Fibres: These are the most basic type, typically manufactured as straight, smooth filaments as shown in fig 1. They offer good mechanical properties and are used in various applications requiring reinforcement against cracking and increased tensile strength.

Fig. 1 Straight steel fibres

3.Hooked-End Steel fibres: These fibres have small hooked ends at both or one end of the filament. The hooks increase the anchorage within the concrete matrix, enhancing pull-out resistance and improving the bond between the fibre and the concrete. There are three varieties of hooked-end steel fibres available in the market. Their geometries are shown in fig. 3.

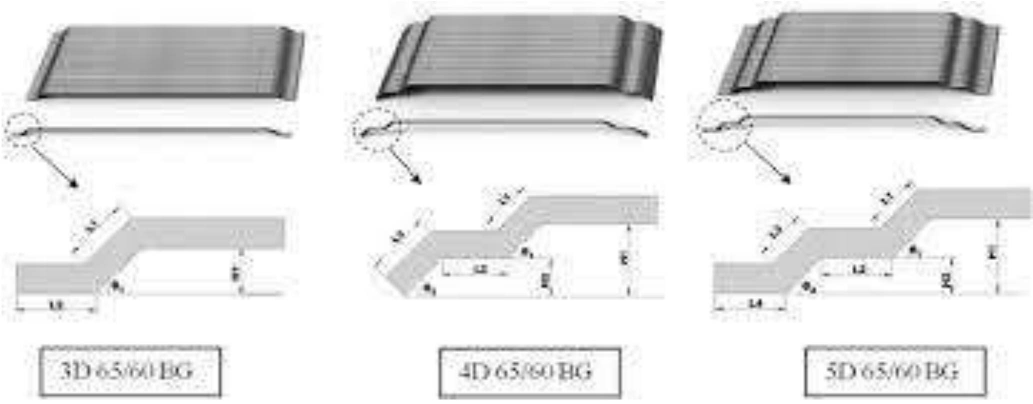

Fig. 3 (a) 3D steel fibre, (b) 4D steel fibre, (c) 5D steel fibre

2.Deformed Steel fibres: These fibres have surface irregularities or deformations as shown in fig. 2 that enhance their bond with the concrete matrix. The deformations can be in the form of hooks, waves, or crimps, providing better interlocking with the concrete, thus improving the overall performance.

Fig. 2 Deformed steel fibres

4.Micro Steel fibres: These fibres are much smaller in diameter compared to conventional steel fibres and are often used in applications where a very fine reinforcement is needed, such as thin-section concrete elements or overlays as shown in fig. 4.

Fig. 4 Micro steel fibres.

2. STEEL FIBRE REINFORCED CONCRETE (SFRC):

Steel fibre reinforced concrete (SFRC) is a type of concrete that incorporates steel fibres into the mixture. These fibres, typically made of stainless steel, carbon steel, or other alloys, are added to the concrete mix to enhance its structural properties. The addition of steel fibres helps in improving the toughness, durability, and tensile strength of the concrete. To improve SFRC's workability and stability, superplasticizers (chemical admixtures) are often added to the concrete mix. In most cases, SFs serve as secondary reinforcement alongside conventional steel bars or prestressing strands acting as primary reinforcement. However, when the SF volume fraction exceeds 2% per volume of concrete, the excellent mechanical properties of SFs might allow for standalone use without continuous reinforcement, yet these materials are typically reserved for specialized applications due to processing limitations and higher costs (Singh, 2017). The mechanical and durability properties of steel fibres are as follows.

3. MECHANICAL PROPERTIES OF STEEL FIBRE REINFORCED CONCRETE

3.1. COMPRESSIVE STRENGTH

Stress-strain curves illustrate an evident improvement in compressive strength, spalling resistance, ductility, and toughness within SFRC (Padmarajaiah and Ramaswamy, 2002). The addition of steel fibres leads to an observed increase in compressive strength ranging from 11% to 24% (Shende et al., 2012). SFRC incorporating up to 1.5% SFs by volume led to a notable enhancement in compressive strength, ranging from 0 to 15% (Dixon & Mayfield, 1971).

3.2. TENSILE STRENGTH

The introduction of 1.5% by volume of SFs can notably enhance the direct tensile strength of concrete by up to 40% (Williamson, 1974). In cases where fibres are distributed more randomly, the observed increase in strength varies, ranging from negligible improvements to approximately 60%, with various studies presenting intermediate values (devi & Singh, 2013). Consequently, the sole aim of adding fibres to elevate direct tensile strength might not be as beneficial. However, as in compression, steel fibres play a crucial role in significantly enhancing post-cracking behaviour or toughness.

3.3. IMPACT RESISTANCE

SFRC displays remarkable resistance to dynamic loads from dropped weights or explosives, exhibiting a striking 8 to 10 times higher impact resistance compared to plain concrete (Singh, 2017). In particular, test findings from specimens incorporating high-tensile-strength, crimped SFs with a 0.50mm diameter showcased an astounding improvement in concrete toughness, surpassing 400% under impact loading (Singh, 2017).

3.4. FLEXURAL STRENGTH

The beams which were fabricated using Dramix RC-65/35-BN type SFs, incorporating two different dosages: 60 kg/m³ and 100 kg/m³ shows that the ratio of the measured ultimate load to the theoretical ultimate load was higher for SFRC beams with the dosage of 60 kg/m³. This suggests that beams with the lower dosage of SFs exhibited a more favourable ratio between the actual and theoretical ultimate loads (Hartman, 1999).

The impact of SFs on concrete flexural strength surpasses their influence on direct tension or compression (Hartman, 1987). There is a substantial increase of approximately 55% in the flexural strength of SFRC with the addition of 2% SFs (Oh et al.,1999). The flexural strength of SFRC rises in tandem with the increase in both fibre volume fraction and age. Furthermore, an escalating aspect ratio contributes to the enhancement of bending strength (Zheng et al., 2023b).

3.5. SHEAR STRENGTH

SFRC containing just 1% by volume of SFs displayed an ultimate shear strength boost of up to 170% compared to SF-less RC (Narayanan and Darwish, 1987). Notably, SFs can serve as a viable alternative to traditional transverse shear reinforcement, potentially replacing it entirely (Noghabai, 2000; Williamson, 1978). Furthermore, using a blend of SFs with diverse aspect ratios proves more effective in enhancing the mechanical performance of SFRC than relying solely on one type of fibre (Noghabai, 2000). Shear strength of SFRC shows a substantial increase due to the addition of SFs (Oh et al., 1999; Narayanan and Darwish, 1987).

4. FLEXURAL BEHAVIOUR OF SFRC BEAMS

Introducing 1.0% by volume of SFs into RC beams heightens both the initial cracking strength and toughness while augmenting the ductility and stiffness of SFRC beams appreciably compared to conventional RC beams lacking SF additions (Behbahani, 1998). The impact of introducing 1.0% by the volume of steel fibre is more evident in RC beams designed from higher compressive strength concrete in contrast to those made from lower compressive strength concrete, owing to the superior bond between fibres and the concrete paste. Implementing 1.0% by volume of SFs in RC beams shows better results in enhancing their flexural behaviour (Behbahani, 1998).

Fibres notably improve performance under service conditions by augmenting stiffness during the cracked stage. This effectively restrains crack openings and deformations.

Beams with high levels of reinforcement in their fibres prevent sudden concrete collapses by notably increasing concrete toughness under compression, which relies on the quantity and properties of these fibres. (Meda et al., 2012).

The strength to withstand bending was directly linked to the reinforcement ratio, whereas the normalized total crack length showed an inverse correlation. This reverse connection can be attributed to the stabilizing effect of crack bridging induced by the longitudinal reinforcement, enabling stable crack expansion (Gümüş & Arslan, 2023).

When comparing beams with identical reinforcements, it's evident that the ultimate moments of SFRC beams are significantly greater than those of Plain concrete beams. This difference can be attributed to the utilization of high-strength steel-fibre-reinforced concrete (Lu et al., 2022).

The inclusion of hooked-end steel fibres resulted in enhancements across various aspects: it improved cracking resistance, boosted stiffness after cracking (reducing service deflection by 21%), increased flexural capacity (raising the maximum load by 40%), and improved ductility (with a 49% increase). These improvements stemmed from reinforced tension, better management of drying shrinkage, increased toughness, and enhancements in post-peak behaviour within the compressive zone (Tran et al., 2019). Increased fibre contents led to improvements in cracked stiffness, and all beams showcased plastic rotation capacities that exceeded their limits (Cardoso et al., 2019).

The ratio between cracking moment and ultimate moment decreased as the reinforcement ratio increased in both RC beams, regardless of the type of fibres used, at reinforcement ratios of 0.33% and 0.50% (Gümüş & Arslan, 2019). Enhancing the distribution and orientation of fibres yields better flexural performance compared to simply increasing the fibre content (Raju et al., 2020).

5. DURABILITY PROPERTIES OF STEEL FIBRE REINFORCED CONCRETE

5.1 ACID ATTACK

When SFRC specimens are immersed in acid for 28 days, weight loss tends to be higher as the fibre dosage is increased in comparison with the conventional concrete. Compressive strength decreases with increase in fibre dosage (Krishna & Rao, 2016). Extended exposure to acid leads to a decrease in concrete strength for specific steel fibre concentrations. This weakening is due to the interaction of gypsum, formed by the reaction between calcium hydroxide and sulfuric acid, with tricalcium aluminate and water, resulting in the creation of expansive ettringite and consequent formation of cracks (Arjomandi et al., 2023). Steel fibre dosage of 1.5% has shown positive effect in resistance to acid attack (Wang et al., 2017). As the dosage of fibres increases in SFRC, the percentage of reduction in compressive strength following 28 and 56 days of acid immersion rises due to the corrosion of steel fibres (Ramakrishnan et al., 2022).

5.2 WATER ABSORPTION

In comparison to the water absorption of specimens cured for 28 days, the SFRC specimens cured for three years displayed a notable reduction, ranging between 3% and 52.4%. This decrease is attributed to the subsequent hydration reaction that densified the internal structure of the concrete (Yuan & Yang, 2022). The open porosity of Steel fibre reinforced concrete marginally exceeded that of conventional concrete. Specifically, the average porosity of conventional concrete measured at 10.7%, while SFRC recorded 11.3%, indicating a difference of approximately 5.6% higher in the latter (C. Frazão et al., 2013).

5.3 CHLORIDE PENETRATION

The rapid chloride permeability test revealed enhanced durability in steel fibre reinforced concrete due to their demonstrated ability to limit chloride penetration into the concrete. The presence of steel fibre reduced concrete cracks by interconnecting the voids within it (Ramakrishnan et al., 2022). Concerning chloride migration, incorporating fibre volumes between 0.5% and 1.5% resulted in a beneficial impact, reducing the depth of chloride penetration from 6.34 to 4.75 mm (Sukontasukkul et al., 2023). The resistance of concrete to chloride-ion penetration when using microfibers is primarily associated with the volume fraction of the fibres. A greater volume fraction of microfibers may escalate the diffusion of chloride ions in concrete, while a lower volume fraction enhances the concrete's ability to resist chloride penetration (Chen et al., 2021). Incorporating an appropriate quantity of SF can impede the ingress of chloride ions. Within a certain range, the greater the dosage of SF, the stronger the inhibitory impact, as SF diminishes the rate at which chloride ions penetrate (Zheng et al., 2023).

5.4 CORROSION RESISTANCE

Corrosion in concrete structures is notably less severe in SFRC compared to conventional concrete, as identified by various studies (Mangat and Gurusamy, 1987; Williamson and Morse, 1977; Halvorsen et al., 1976; Aufmuth et al., 1974). The well-compacted SFRC experiences limited corrosion of fibres near the concrete surface, even when the concrete is highly saturated with chloride ions (Schupack, 1985).

When prismatic SFRC specimens containing hooked-end SFs are exposed to marine-like environment for a year and tested in a three-point bending setup, it was observed that only SFs crossing the crack within a 2 to 3mm rim from the external faces of the specimens exhibited extensive corrosion. Limited or no SF corrosion was noticed in narrower crack parts (0.1mm crack mouth opening), while wider crack sections (0.5mm crack mouth opening) showed slight fibre corrosion without a reduction in their section. No concrete bursting or spalling was recorded due to fibre corrosion (Turatsinze et al., 2005).

6. CONCLUSION:

The paper provides an overview of Steel Fibre Reinforced Concrete (SFRC), emphasizing its mechanical properties, advantages, and applications. Over recent decades, substantial advancements have been achieved in concrete technology, notably in the realm of Fibre Reinforced Concrete. SFRC is defined as a composite material wherein conventional concrete is strengthened by the random dispersion of short, discontinuous, and discrete fine Steel fibres with specific geometries. Unlike traditional reinforcing steel bars, which are strategically designed and placed in the concrete's tensile zone, fibres are thin, short, and dispersed randomly throughout the concrete member. Among various types of fibres utilized for concrete reinforcement, Steel fibres stand out as the most popular choice. The performance of Steel fibre Reinforced Concrete (SFRC) has exhibited remarkable enhancements in flexural strength and overall toughness when compared to Conventional Reinforced Concrete.

REFERENCES

1. Gümüş, M., & Arslan, A. (2023). Cracking behavior and flexural capacity prediction of singly reinforced RC beams with and without steel fibre. *Theoretical and Applied Fracture Mechanics*, *124*, 103790. https://doi.org/10.1016/j.tafmec.2023.103790

2. Minglei Zhao, Changyong Li, Jie Li, Lixian Yue, Experimental study on performance of steel fiber reinforced concrete for remote-pumping. construction. Materials 2023,16, 366

3. Lu, C., Cai, Q., Xu, K., Sha, X., & Yan, Y. (2022). Comparison of flexural behaviors between plain and steel-fiber-reinforced concrete beams with hybrid GFRP and steel bars. *Structures*, *43*, 1–11. https://doi.org/10.1016/j.istruc.2022.06.037

4. More, D., & Selvan, S. S. (2021). Experimental study on addition of Steel Fibres in Conventional Concrete, *IOP Conference Series*, *1130*(1), 012044. https://doi.org/10.1088/1757-899x/1130/1/012044

5. Raju, V Kesava and Srinivasa Rao, K., Compressive Behaviour of Standard Concrete and Steel Fibre Reinforced Standard Concrete at High Temperatures (March 10, 2020). International Journal of Advanced Research in Engineering and Technology (IJARET), 11 (2), 2020, pp 67-76

6. Cardoso, D. C., Pereira, G. B. S., Da Silva, F. A., Filho, J. J. H. S., & Pereira, E. A. (2019). Influence of steel fibers on the flexural behavior of RC beams with low reinforcing ratios: Analytical and experimental investigation. *Composite Structures*, *222*, 110926. https://doi.org/10.1016/j.compstruct.2019.110926

7. Gümüş, M., & Arslan, A. (2019c). Effect of fiber type and content on the flexural behavior of high strength concrete beams with low reinforcement ratios. *Structures*, *20*, 1–10. https://doi.org/10.1016/j.istruc.2019.02.018

8. Marcos-Meson, V., Fischer, G., Edvardsen, C., Skovhus, T. L., & Michel, A. (2019). Durability of Steel Fibre Reinforced Concrete (SFRC) exposed to acid attack – A literature review. *Construction and Building Materials*, *200*, 490–501. https://doi.org/10.1016/j.conbuildmat.2018.12.051

9. Tran, T. T., Pham, T. M., & Hao, H. (2019). Experimental and analytical investigation on flexural behaviour of ambient cured geopolymer concrete beams reinforced with steel fibers. *Engineering Structures*, *200*, 109707. https://doi.org/10.1016/j.engstruct.2019.109707

10. Yoo, D., & Moon, D. (2018). Effect of steel fibers on the flexural behavior of RC beams with very low reinforcement ratios. *Construction and Building Materials*, *188*, 237–254. https://doi.org/10.1016/j.conbuildmat.2018.08.099

11. Arul Raj C, Baskar K, Experimental Investigation On Flexural Behaviour Of Steel Fibre And Nylon Fibre Reinforced Concrete Beam, *SSRG International journal of civil engineering – (ICRTCETM-2017)*

12. Anurag Mishra, Prof. Kirti Chandraul, Prof. Manindra Kumar Singh ,Experimental study on steel fibre reinforced concrete, Volume: 04 Issue: 11 | Nov -2017

13. Krishna, P., & Rao, N. (2016). Durability Studies on Steel Fiber Reinforced Concrete. *International Research Journal of Engineering and Technology (IRJET)*, *3*(8).

14. Venkata Siva Abhilash, Gogineni & Jagarapu, Durga Chaitanya Kumar & Sai, G & Ram, V & Khan, P.. (2016). EXPERIMENTAL STUDY ON STEEL FIBER CONCRETE. 10.13140/RG.2.2.29409.84325

15. Zhang, H., & Pei, C. (2015). The Study on Mechanical Properties of Cement Mortar with Different Types of Steel Fibers. *International Congress of Mathematicans*.

16. H.C. Mertol, E. Baran, H.J. Bello, Flexural behavior of lightly and heavily reinforced steel fiber concrete beams, Constr Build Mater, 98 (2015), pp. 185-193

17. Błaszczyński, T., & Przybylska-Fałek, M. (2015). Steel Fibre Reinforced Concrete as a Structural Material. *Procedia Engineering*, *122*, 282–289. https://doi.org/10.1016/j.proeng.2015.10.037

18. Ghaffar, A., Chavhan, A.S., & Tatwawadi, D. (2014). Steel Fibre Reinforced Concrete. *international journal of engineering trends and technology, 9*, 791-797
19. Frazão, C. M. V., Camões, A., Barros, J. a. O., & Gonçalves, D. (2015). Durability of steel fiber reinforced self-compacting concrete. *Construction and Building Materials*, *80*, 155–166. https://doi.org/10.1016/j.conbuildmat.2015.01.061
20. Richardson, A., & Heather, M. (2013). Improving the Performance of Concrete using 3D Fibres. *Procedia Engineering*, *51*, 101–109. https://doi.org/10.1016/j.proeng.2013.01.016
21. Shende, Pande, & Pathan, M. (2012). Experimental Study on Steel Fiber Reinforced Concrete for M-40 Grade. *International Refereed Journal of Engineering and Science (IRJES)*, *1*(1).
22. devi, T., & Singh, T. (2013, October). Effects Of Steel Fibres in Reinforced Concrete. International Journal of Engineering Research & Technology (IJERT).
23. Singh. (2017, January). STEEL FIBER REINFORCED CONCRETE. International Journal of Advance Research in Science and Engineering.
24. Behbahani, Hamid. (1998). Flexural behavior of steel fiber reinforced concrete beams. Journal of Materials in Civil Engineering. 10. 10.1061/(ASCE)0899-1561(1998)10:2(86).
25. Meda, A., Minelli, F., & Plizzari, G. (2012). Flexural behaviour of RC beams in fibre reinforced concrete. *Composites Part B: Engineering*, *43*(8), 2930–2937. https://doi.org/10.1016/j.compositesb.2012.06.003
26. Raju, R. A., Lim, S., Akiyama, M., & Kageyama, T. (2020). Effects of concrete flow on the distribution and orientation of fibers and flexural behavior of steel fiber-reinforced self-compacting concrete beams. *Construction and Building Materials*, *262*, 119963. https://doi.org/10.1016/j.conbuildmat.2020.119963
27. Milind V. Mohod, Performance of Steel Fiber Reinforced Concrete, International Journal of Engineering and Science ISSN: 2278-4721, Vol. 1, Issue 12 (December 2012), PP 01-04
28. Abid, Sallal. (2007). Strength and Elasticity of Steel Fiber Reinforced Concrete at High Temperatures. Journal of Engineering and Development. 11. 125-130.
29. Johnston, C.D, Colin, D. (1982). “Fibre Reinforced Concrete.” Progress in Concrete Technology CANMET, Energy, Mines and Resources, Canada, pp 215-236.
30. Narayanan, R., and Darwish, I. (1987). “Bond Anchorage of Pretentioned FRP Tendon at Force Release.”ASCE Journal of Structural Engineering,118:No.10,pp 2837-2854.
31. Noghabai, K. (2000). Beams of Fiberous Concrete in Shear and Bending: Experiment and Model. Journal of Structural Engineering ,ASCE, Vol.126,No.2,pp 243-251.
32. Ocean concrete products, Ocean Heidelberg Cement Group (1999). Steel Fibre Reinforcement – Working Together to Build Our Communities Report.
33. Oh,S.G., Noguchi T. and Tomosawa,F. (1999). “Evaluation of Rheological Constants of HighFluidity Concrete by Using the Thickness of Excess Paste.” Journal of the Society of Materials Science, August, Japan.
34. Padmarajaiah, S. & Ramaswamy, A. 2002. A finite element assessment of flexural strength of prestressed concrete beams with fiber reinforcement. Cement and Concrete Composites, 24, 229-241.
35. Rapoport, J., Aldea, C., Shah,S.p., Ankenman, B., and Karr, A.F. (2001). Permeability of Cracked Steel Fiber-Reinforced Concrete.Technical Report No.115, National Institute of Statistical Sciences(NISS),Research Triangle Park,NC,USA.
36. Romualdi, J. & Baston, G. 1963. Mechanics of crack arrest in concrete with closely spaced reinforcement. Journal of the Engineering Mechanics Division., EM3. Proceedings of the American Society of Civil Engineers, 89, 147-168.
37. Schupack, M. (1985). Durability of SFRC Exposed to Sever Environments. Proceedings. Steel Fiber Concrete US-Sweden Joint Seminar (NSF-STU),Swedish Cement and Concrete Research Institute, Stockholm/Sweden,June,pp479-496.
38. Tsai, C. T., Li, L. S., Chang, C. C. & Hwang, C. L. 2009. Durability Design and Application of Steel Fiber Reinforced Concrete in Taiwan. Arabian Journal for Science and Engineering, 34.
39. Turatsinze, A., Granju, J. L., Sabathier, V. & Farhat, H. 2005. Durability of bonded cement-based overlays: effect of metal fibre reinforcement. Materials and structures, 38, 321-327.
40. Wiliamson, G.R (1978). Steel Fibers as Reinforcement in Reinforced Concrete. Proceeding, US Army Science Conference, West Point, Vol.3, pp 363-377.

41. Wiliamson, G.R. (1974). The Effect of Steel Fibers on Compressive Strength of Concrete,Fiber Reinforced Concrete.SP-44.ACI,pp 195-207, Detroit.Michigan, USA.
42. Williamson, G. & Morse, D. 1977. Corrosion Behavior of Steel Fibrous Concrete. Construction Engineering Research Lab (Army) Champaign Ill.
43. Woodrow, T. (1980). Marine Durability Survey of the Tongue Sands Tower. Concrete in the Oceans Technical Report No. 5, Taylor Woodrow Research Laboratories, Canada.
44. ACI 544.1R (1996). State-of-the-Art Report on Fiber Reinforced Concrete, American Concrete Institute, Farmington Hills, Michigan.
45. Aufmuth, R.E, Naus, D.G , Williamson, G.R. (1974). Effect of Aggressive Environment on Steel Fibre Reinforced Concrete, Letter Report M-113.US Army Corps of Engineers. Construction, Engineering Research Laboratory, Chaimpaign, IL.
46. Dixon, J. & Mayfield, B. 1971. Concrete reinforced with fibrous wire. Journal of the Concrete Society, Concrete, 5, 73-76.
47. F. Altun et al. (2006) “Effects of steel fiber addition on mechanical properties of concrete and RC beams” Construction and Building Materials 21: 654–661.
48. Gambhir, M.L. (1995). Concrete Technology. (2nd Eddition).,NEW DELHI.Tata McGraw-Hill.
49. Grzybowski, M. (1989). Determination of Crack Arresting Properties of Fiber Reinforced Cementitious Composites. Chapter 12, Royal Institute of Technology, Stockholm, Sweden.
50. Grzybowski, M. & Shah, S. P. 1990. Shrinkage cracking of fiber reinforced concrete. ACI Materials Journal, 87.
51. Hannant, D.J. (1978).Fiber Cements and Fiber Concrete. John Wiley and Sons Ltd., Chichester, UK, pp 53.
52. Hartman, T. (1999). Steel Fiber Reinforced Concrete. Master Thesis., Department of Structural Engineering. Royal Institute of Technology, Stockholm, Sweden
53. Arjomandi, A., Mousavi, R., Tayebi, M., Nematzadeh, M., Gholampour, A., Aminian, A., & Gençel, O. (2023). The effect of sulfuric acid attack on mechanical properties of steel fiber-reinforced concrete containing waste nylon aggregates: Experiments and RSM-based optimization. *Journal of Building Engineering*, *64*, 105500. https://doi.org/10.1016/j.jobe.2022.105500
54. Wang, Yan & Niu, Ditao & Zhanping, Song. (2017). Effect of acid rain erosion on steel fiber reinforced concrete. Journal of Wuhan University of Technology-Mater. Sci. Ed.. 32. 121-128. 10.1007/s11595-017-1569-y.
55. Ramakrishnan, S., Dinesh, A., Gnanaprabhakaran, M., Aswin, D., & Gowthambalaji, K. (2022). Investigation on durability of study Fiber reinforced concrete. *IOP Conference Series*, *1125*(1), 012018. https://doi.org/10.1088/1755-1315/1125/1/012018
56. Sukontasukkul, P., Intarabut, D., Phoo-Ngernkham, T., Suksiripattanapong, C., Zhang, H., & Chindaprasirt, P. (2023). Self-compacting steel fibers reinforced geopolymer: Study on mechanical properties and durability against acid and chloride attacks. *Case Studies in Construction Materials*, *19*, e02298. https://doi.org/10.1016/j.cscm.2023.e02298
57. Chen, W., Zhu, H., He, Z., Yang, L., Zhao, L., & Wen, C. (2021). Experimental investigation on chloride-ion penetration resistance of slag containing fiber-reinforced concrete under drying-wetting cycles. *Construction and Building Materials*, *274*, 121829. https://doi.org/10.1016/j.conbuildmat.2020.121829
58. Yuan, Z., & Yang, J. (2022). Experimental study on the mechanical properties, water absorption, and fiber degradation of naturally aged glass fiber and polypropylene Fiber-Reinforced concrete. *Materials*, *15*(11), 3760. https://doi.org/10.3390/ma15113760
59. Zheng, Y., Lv, X., Hu, S., Zhuo, J., Wei, C., & Liu, J. (2023). Mechanical properties and durability of steel fiber reinforced concrete: A review. *Journal of Building Engineering*, 108025. https://doi.org/10.1016/j.jobe.2023.108025