

Influence of polypropylene fiber with Styrene-Butadiene Rubber Latex bonding agent in prevention of early crack of concrete

Shaik Shahid Ali¹, Anil Kunte² and Aashis S Roy^{3*}

¹ Department of Civil Engineering, Shri Jagdishprasad Jhabarmal Tibrewala University, Vidyanagari, Jhunjhunu, Rajasthan-333001, India

² Department of Civil Engineering, Shri Jagdishprasad Jhabarmal Tibrewala University, Vidyanagari, Jhunjhunu, Rajasthan-333001, India

³ Department of Chemistry, S.S.Tegoor Degree College, Gubbi Colony – 585104, India

Author correspondence: Aashis S Roy

Email: aashisroy@gmail.com; **Phone:** +919108809031

Abstract

We have fabricated the concrete reinforced polypropylene fiber with styrene-butadiene rubber latex bonding agent of concrete in different ratio. The prepared concrete employed with structural studies using FTIR and XRD spectra. An FTIR spectrum shows the important characteristics peaks of polypropylene fiber and styrene-butadiene rubber along with silica peaks. XRD pattern indicates that concrete crystal structure of three polymorphs such orthorhombic, triclinic and monoclinic phase. SEM image indicates that the above 10 wt % of polypropylene fiber causes small hairline cracks on its surface. It is found that the tensile strength increases with increase in different weight percentage of polypropylene fiber up to 10 wt %. This is may be due to the high compactness and reduction in porosity of the concrete block. It is also important to note that the water reduce admixture such as Polycarboxylates in required ratio's significantly effects on capillary threshold by reducing 8-12 % of water results higher density of the concrete.

Keywords: Polypropylene fiber, Concrete, Crystal structure, Surface morphology, Admixture

1. Introduction

Polypropylene fiber is a material that has been widely studied and used in concrete applications. It is known for its high tensile strength and ability to improve concrete's resistance to cracking. Additionally, polypropylene fibers have been found to enhance the freeze-thaw durability of concrete [1]. Styrene-butadiene rubber latex, on the other hand, is a bonding agent that has shown promising results in improving the compressive strength and abrasion resistance of concrete. There are effective measures that can be taken to prevent cracks in concrete and ensure its long-term durability [2].

Polypropylene fiber-based concrete has proven to have a significant impact on the structural integrity and durability of concrete. One study found that at a fiber content of 0.15%, both

internal and surface cracks in concrete were positively affected after 56 cycles, indicating improved crack resistance and durability [3]. Additionally, the incorporation of polypropylene fiber at this content level resulted in a higher level of structural integrity and durability in the concrete. The use of synthetic organic fibers, such as polypropylene fiber, has also been found to reduce shrinkage cracks in concrete and improve its working performance and ductility. Furthermore, polypropylene fiber-based concrete has been shown to enhance the wear resistance, impermeability, and tensile strength of fiber-reinforced high-performance concrete [4]. In terms of erosion resistance, adding 0.15% polypropylene fiber to both fresh water and seawater concretes increased their drying-wetting erosion resistance by 46% and 49% respectively. However, it is important to note that excessive fiber incorporation can lead to clumping and entanglement of the fibers, compromising their efficiency in reducing the porosity of the concrete [5]. Overall, the inclusion of polypropylene fiber in concrete has a dominant effect on controlling the development of micro-cracks in the early stages, improving the crack resistance and durability of structures. Polypropylene fiber is a remarkable material that offers a multitude of benefits across various industries. Its properties make it an ideal choice for applications where strength, durability, moisture resistance, chemical resistance, and thermal stability are essential [6-8]. One of the key advantages of polypropylene fiber is its exceptional strength. It possesses a high tensile strength, allowing it to withstand heavy loads and resist breaking or tearing under pressure. This makes it an excellent choice for applications where strength and durability are critical, such as in the manufacturing of ropes, geotextiles, and automotive components [9].

In this study, T. Aly et al. (2008) [10] discuss their findings on the impact of admixed polypropylene (PP) fibres on the drying shrinkage of hardened concrete. Various volume fractions of PP fibre in concrete mixtures prepared with ordinary Portland cement (OPC) and OPC/Slag blended cements were studied. The findings indicate that concretes with PP fibres exhibit slightly but consistently larger drying shrinkages than concretes without fibre. The impact is particularly noticeable in slag concrete and in one-day-cured concrete. The identical concretes were tested for water loss, nitrogen adsorption, sorptivity, and scanning electron microscopy in an effort to understand this phenomenon. Porosity and further moisture loss are suggested as potential causes. Early-age restricted shrinkage tests on slag concretes' results reveal that the PP fibre concrete cracked more frequently than the concrete without fibre. This was discovered to be caused by the increased elastic modulus and shrinkage of PP fibre concrete.

In addition to its impressive strength, polypropylene fiber also exhibits outstanding durability. It can withstand exposure to harsh environmental conditions without losing its integrity or performance. Whether it's exposed to extreme temperatures or outdoor elements like UV radiation, polypropylene fiber remains unaffected by these factors [11]. This makes it highly suitable for outdoor applications such as outdoor furniture upholstery or synthetic turf. Moreover, polypropylene fiber boasts excellent moisture resistance. It does not absorb water easily and is resistant to rotting or mildew growth when exposed to moisture. This

property makes it ideal for use in products that require protection against moisture damage, like carpets and upholstery fabrics [12]. Another noteworthy characteristic of polypropylene fiber is its chemical resistance. It can resist the effects of various chemicals such as acids and bases, making it suitable for applications in industries that deal with corrosive substances or hazardous materials [13].

The unique properties of polypropylene fiber make it a versatile material across multiple industries. Its exceptional strength, durability, moisture resistance, chemical resistance, and thermal stability make it an ideal choice for various applications ranging from textiles to construction materials [14 - 17]. By utilizing polypropylene fiber in concrete can enhance the quality and performance while ensuring long-lasting durability in demanding environments.

We have investigated the fabrication of polypropylene fiber based concrete with different admixture and bonding agent. The prepared concrete blocks subjected to the structural studies using FTIR and XRD spectra and surface morphology were studied using scanning electron microscopy. The mechanical studies were carried out by using universal testing machine.

2. Materials and Methods

In the experiment, regular Portland cement with a grade of 42.5 was employed. Mixing machine-made sand with a fineness modulus of 4.4 and natural sand with a fineness modulus of 1.4 produced the fine aggregate with a fineness modulus of 2.8. As a chemical additive, the high-performance polycarboxylate for water reduction and styrene butadiene copolymer rubber latex (SBR) as a binding agent were used. The concrete mix contained tap water.

2.1 Preparation of reinforced concrete

For three different percentage polypropylene fiber dosages and two distinct mix ratios, a total of ten mortar roads were cast. Cement to sand ratios of 1:3 and 1:4 were used in the mortar compositions. Different dosages of polymer (0, 5, 10, & 15%) were used in the reinforced concretes, which were cast for the same flow level. with each mix ratio of 1:3 and 1:4, four mortar slabs were kept out of the direct heat of the sun whereas three mortar slabs with a mix ratio of 1:3 (cement:sand) were exposed to it. A measuring scale and a magnifying lens were used to measure the shrinkage and cracks. The results of plastic shrinkage at 5 hours and drying shrinkage at 3, 7, and 28 days were studied [18 – 20].

Table 1 shows the polypropylene fiber dosages in concrete mix design

Sl.No	polypropylene fiber	SBR bonding agent	Polycarboxylates
PC0	0 wt %	200 ml per 40 kg of cement concrete	1.6 wt %
PC1	5 wt %	200 ml per 40 kg of cement concrete	1.6 wt %
PC2	10 wt %	200 ml per 40 kg of cement concrete	1.6 wt %
PC3	15 wt %	200 ml per 40 kg of cement concrete	1.6 wt %

3. Results and discussion

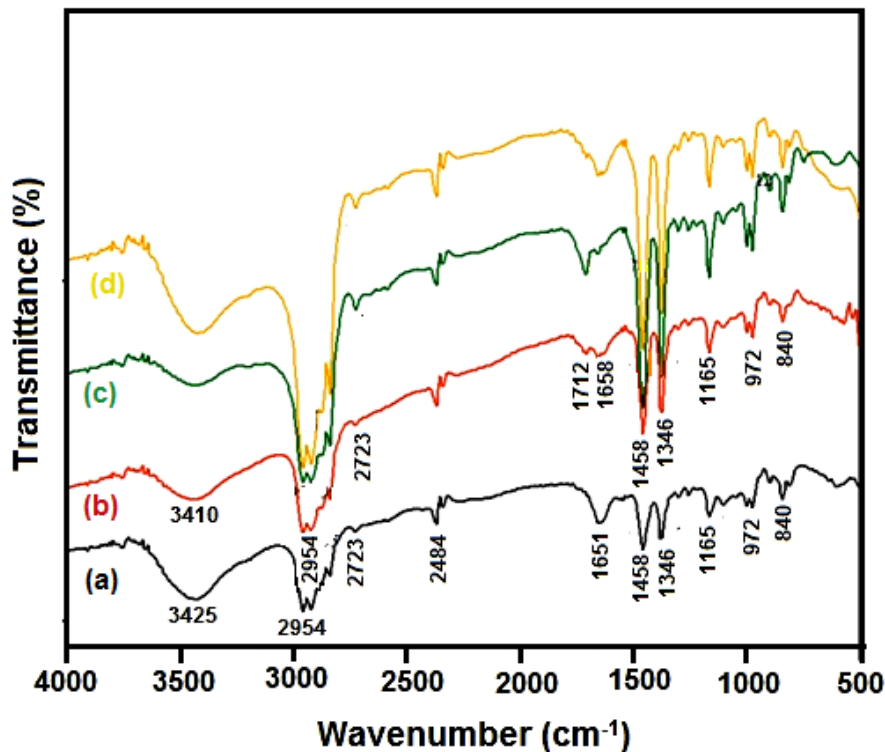


Figure 1 shows FTIR spectra of polypropylene fiber based concrete with bonding agent. The structural properties of the polypropylene fiber based concrete with polypropylene fiber as shown in figure 1. The important characteristics of concrete without admixture peaks are found at 3425cm^{-1} is correspondence to for O – H stretching of hydroxyl ion of water in PC0, 2954 cm^{-1} is due to the H-C-H stretching bending in plane, 2723 cm^{-1} for C-CH₃ stretching in plane, 2484 cm^{-1} for C = O stretching in plane, 1651 cm^{-1} is due to the C – C bending of divinylbenzene plane, 1458 cm^{-1} for C – CH₃ stretching bending in symmetry of the plane, 1346 cm^{-1} for is due to C – CH₂ stretching & bending in plane, 1165 cm^{-1} for C – O stretching symmetry of plane of anhydride, 972 cm^{-1} for H– C –H stretching in plane and 840 cm^{-1} for C – H stretching of aromatic ring. Apart from that PC1, PC2 and PC3 shows the other important peaks at 3410 cm^{-1} for stretching the isopropene butadiene, 1712 cm^{-1} for CH₂ – O – CH₂ for polycarboxlic ether stretching bending in plane, 886 cm^{-1} is due to the styrene group stretching, 548 cm^{-1} is corresponding for Si-O-Si bending of the plane [21 – 23].

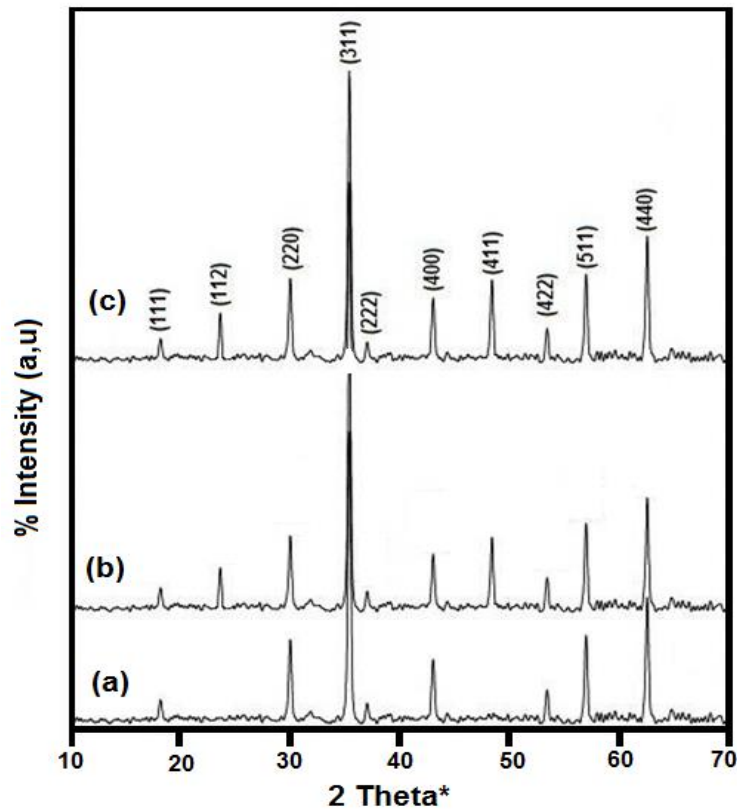


Figure 2 shows XRD pattern of polypropylene fiber based concrete

Figure 2 shows the XRD pattern of polypropylene fiber based concrete with admixture and bonding agent. The XRD pattern of figure 2 (a) shows the important characteristics peak at 18.6, 30.1, 35.2, 36.8, 44.2, 54.2, 58.5, 63.2 corresponds to the (hkl) value of (111), (220), (311), (222), (400), (422), (511) and (440) which implies the formation of orthorhombic and monoclinic phase. However, the figure 2 (b) & (c) indicates the P2 and P3 which shows that the characteristic peaks at 18.6, 24.2, 30.1, 35.2, 36.8, 44.2, 48.6, 54.2, 58.5, 63.2 corresponds to the (hkl) value of (111), (112), (220), (311), (222), (400), (411), (422), (511) and (440) this implies that the concrete formed crystal structure of three polymorphs such orthorhombic, triclinic and monoclinic phase [24 – 26].

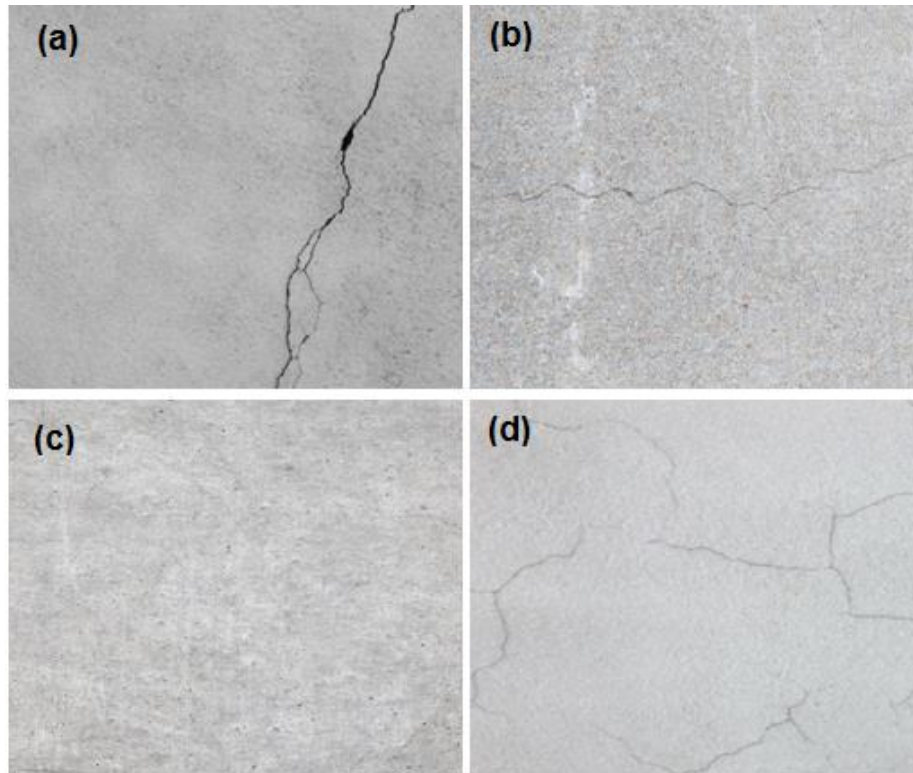


Figure 3 illustrate the concrete surface designed with polypropylene fiber

Figure 3 shows that the concrete surface designed with polypropylene fiber. It is observed that in figure 3(a) fabricated the concrete without polypropylene fiber shows the early stage cracking is plastic shrinkage. As the water evaporates from the surface of fresh concrete, it undergoes volume reduction, leading to tensile stresses that can result in cracks. Figure 3(b – d) shows the polypropylene fiber helps to mitigate this problem by providing additional reinforcement and reducing crack widths. Another factor contributing to early stage cracking is thermal stress. Concrete undergoes significant temperature changes during curing, which can cause differential expansion and contraction within the material. This leads to internal stress buildup and potential crack formation. Polypropylene fibers act as a thermal insulator, reducing heat transfer within the concrete and minimizing thermal stress-induced cracking [27 - 29].

The figure 3(b & d) shows early stage crack formation in polypropylene fiber-based concrete is a complex phenomenon influenced by multiple factors such as plastic shrinkage and thermal stress. The incorporation of polypropylene fibers effectively addresses these issues by enhancing tensile strength, reducing crack widths, and mitigating thermal stresses [30].

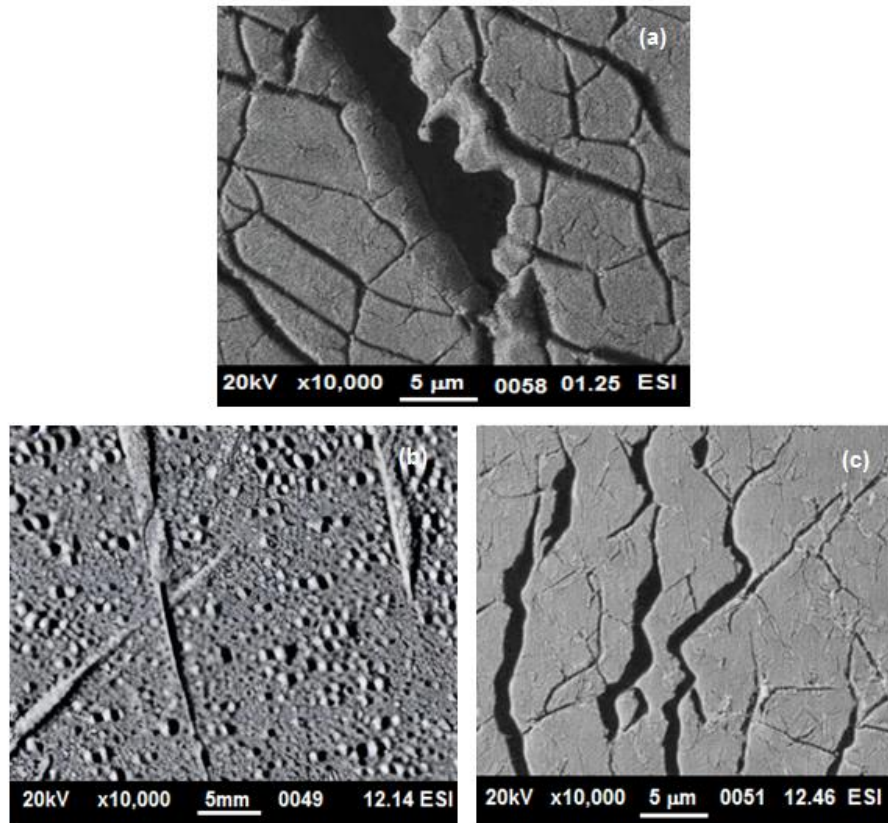


Figure 4 shows SEM image of polypropylene fiber based concrete with bonding agent

The surface morphology of polypropylene fiber based concrete with admixture and bonding agent as shown in figure 4 (a – c). In figure 4 (a) shows that the concrete fabricated without polypropylene fiber designated as PC0, shows that the many early stage cracks due to the plastic shrinkage and thermal stress. However, it is observed that the water effectively reduced causes affective increase in mechanical strength [31]. Figure 4 (b) is fabricated by mix designed polypropylene fiber based concrete in presence of Polycarboxylates ether and SBR latex significantly helps to prevent the early cracks on the surface of concrete and have very good mechanical strength. However, it is observed that the above 10 wt % of polypropylene fiber causes small hairline cracks on its surface as shown in figure 4 (c).

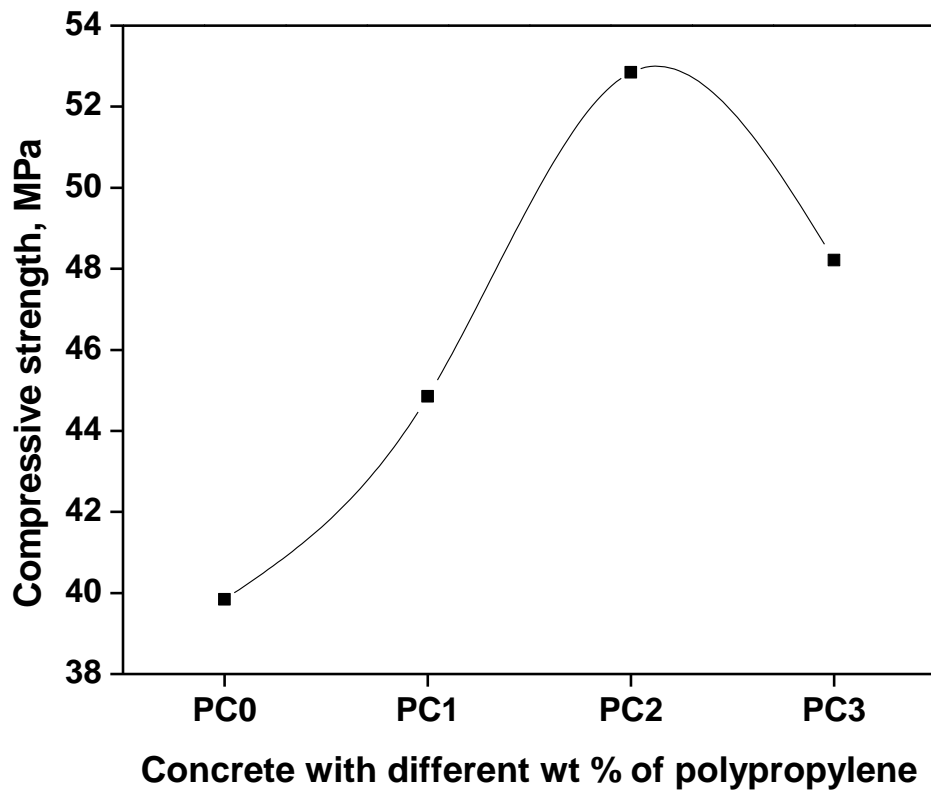


Figure 5 shows that the variation of compressive strength

The variation of compressive strength against different weight percentage of polypropylene fiber concrete with polycarboxylates as super plasticizer as shown figure 5. It is observed that the compressive strength of the concrete increases with increase in polypropylene fiber up to 10 wt % in the concrete. The polypropylene fibers which are compatible with concrete mixture enhance the sharing strength as well as the compressive strength may be due to the formation of fiber volume fraction network throughout the matrix [32]. It is found that after 10 wt % of the fibers mixed with concrete produce small surface cracks may be due to the higher volume fraction and another reason for high compressive strength of the 10 wt % of polypropylene has high compactness and less porosity. Moreover, the positive affect of reinforcement with polypropylene fibers on compressive strength increases as the age of the concrete pavement increases. It is worth noting that the maximum allowable content of polypropylene fibers in concrete is 10 % of the concrete volume. Overall, polypropylene fiber reinforcement offers several advantages in terms of cost-effectiveness and improving the mechanical properties of concrete [33].

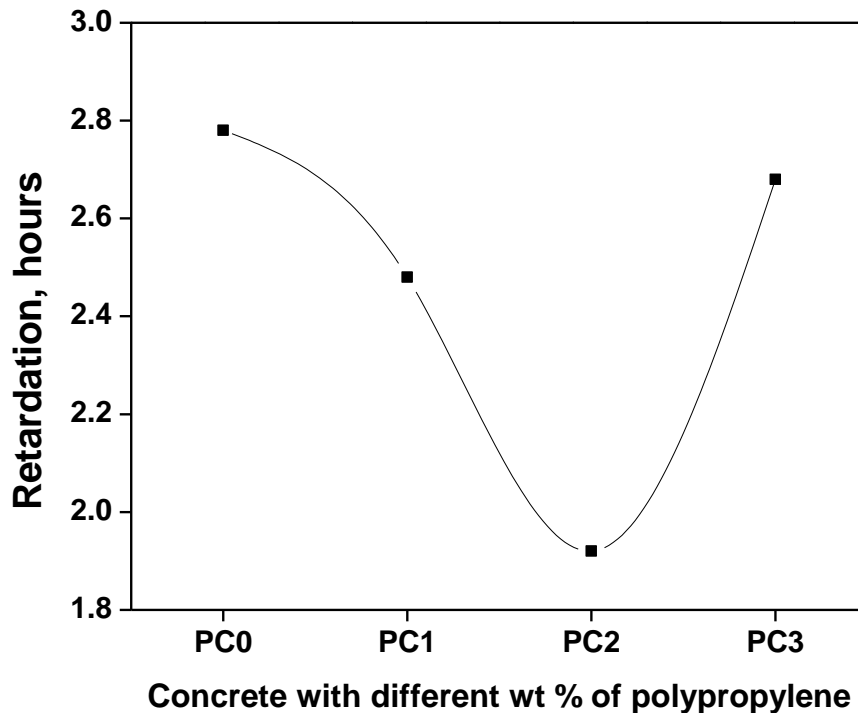


Figure 6 show that the variation retardation of polypropylene fiber mixed concrete

Figure 6 show that the variation retardation of polypropylene fiber mixed concrete with different percentages of admixture. However, the demand for higher-quality structures with improved mechanical properties necessitates the integration of additives like polypropylene fibers. These fibers enhance the durability, crack resistance, and flexural strength of concrete. Nevertheless, the need to achieve adequate workability while incorporating these fibers poses a unique challenge, as their presence often accelerates the setting time. It is observed that the retardation time increases with increase in polypropylene percentages and silicon weight percentages in concrete [34 – 36]. The differences in the water demand affected the hydration products and strength development in these systems. Regarding the microstructure studies, it was revealed that C-Si-H, Si-O-Si, C-S-H and C-A-S-H gels prevail in high calcium and silicon systems, whereas in silicon- and aluminum rich systems (N,C)-A-S-H and C-A-S-H gels predominated. However, the early stage compressive strengths indicated a very promising performance from the application point of view [37].

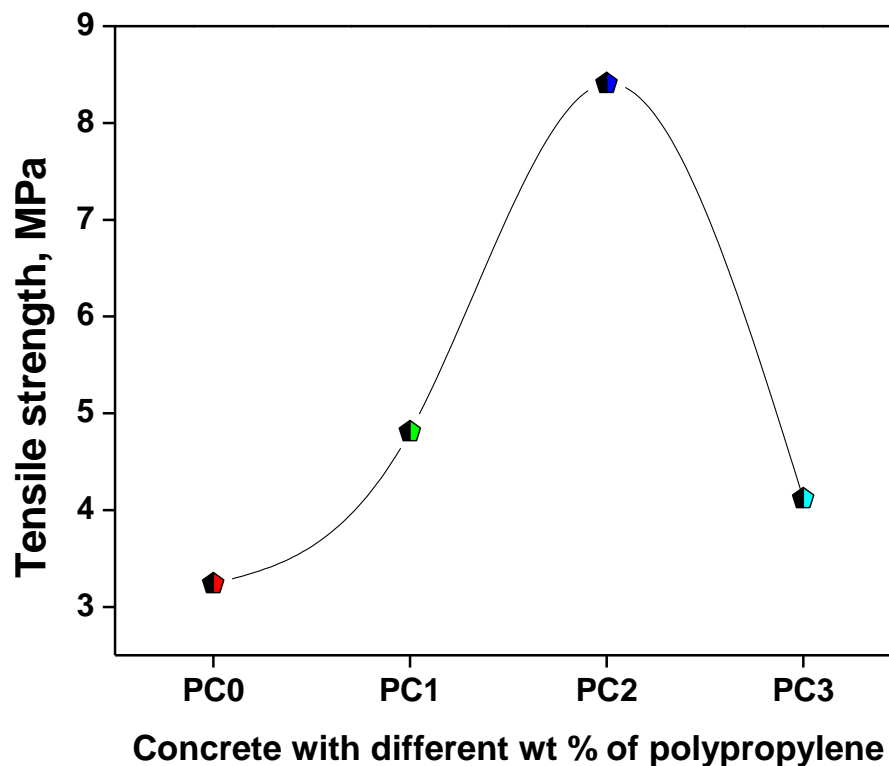


Figure 7 shows that the variation of tensile strength

Figure 7 shows that the variation of tensile strength against different weight percentage of polypropylene fiber in concrete with proper ratio of admixture. However, it is important to note that the addition of polypropylene fibers may initially reduce the tensile strength of concrete at 28 days. Nevertheless, after this initial period, the presence of polypropylene fibers leads to an improvement in the bending tensile strength of concrete, particularly when added at a concentration of 2.5 kg/m^3 . This improvement in bending tensile strength has been observed in comparison to reference concrete without fiber reinforcement [38, 39]. Furthermore, concrete modified with the addition of polypropylene fibers has been found to exhibit better brittleness properties compared to reference concrete and even concrete modified with steel fibers. This suggests that polypropylene fibers can enhance the overall performance and integrity of concrete structures [40]. It is found that the tensile strength increases with increase in different weight percentage of polypropylene fiber up to 10 wt %. This is may be due to the high compactness and reduction in porosity of the concrete block. It is also important to note that the water reduce admixture such as Polycarboxylates in required ratio's significantly effects on capillary threshold by reducing 8-12 % of water results higher density of the concrete.

4. Conclusion

The styrene-butadiene rubber latex bonding agent of concrete was used to produce the concrete-reinforced polypropylene fibre in various ratios. FTIR and XRD spectra were used to analyse the structural analyses of the prepared concrete. Styrene-butadiene rubber and polypropylene fibre, as well as silica peaks, are visible in an FTIR spectrum as major distinctive peaks. Three polymorphs, including orthorhombic, triclinic, and monoclinic phases, are shown by the XRD pattern to make up the concrete crystal structure. According to a SEM photograph, polypropylene fibre content above 10 weight percent causes tiny hairline cracks to form on the material's surface. Up to 10 weight percent of polypropylene fibre, it has been discovered, the tensile strength improves with the increase in weight. The higher volume fraction and another factor for the 10 wt% polypropylene's strong compressive strength is that it has high compactness and low porosity. It is discovered that when fibres are mixed with concrete at 10 wt%, there are minor surface fractures that may be caused by these factors. Additionally, as the age of the concrete pavement grows, the beneficial effects of reinforcement with polypropylene fibres on compressive strength grow. It is important to note that 10% of the volume of concrete can contain a maximum amount of polypropylene fibres. The tensile strength of polypropylene fibre is discovered to grow with increasing weight percentages up to 10 wt%. This might be a result of the concrete block's high compactness and decreased porosity. It is also crucial to keep in mind that decreasing 8–12% of the water in an additive like polycarboxylates has a substantial impact on the capillary threshold and increases the density of the concrete.

5. Reference

- [1]. Julia Blazy, Rafał Blazy, Polypropylene fiber reinforced concrete and its application in creating architectural forms of public spaces, *Case Studies in Construction Materials*, 14 (2021) e00549
- [2]. Zhen Sun, Yalin Li, Yaqi Li, Li Su, Weidong He, Prediction of chloride ion concentration distribution in basalt-polypropylene fiber reinforced concrete based on optimized machine learning algorithm, *Materials Today Communications*, 36 (2023) 106565
- [3]. Zhennan Li, Aiqin Shen, Guopeng Zeng, Zhengtong Chen, Yinchuan Guo, Research progress on properties of basalt fiber-reinforced cement concrete, *Materials Today Communications*, 33, (2022) 104824
- [4]. Qiangqiang Han, Lu Jiang, Yu Zhang, Wenjing Wang, Pengjun Li, Wei Lu, Hua Xia, Zhu Li, Study on crack-healing effect of cement mortar with fiber under dynamic water environment, *Journal of Building Engineering*, 72 (2023) 106567
- [5]. Zhe Chen, Yushi Liu, Mingzhi Wang, Boyi Zhang, Wei Wang, Effect of coarse aggregate grading optimization on temperature, thermal stress and compressive strength

- of carbon fiber-reinforced concrete by ohmic heating curing, *Journal of Building Engineering*, 66 (2023) 105882
- [6]. Jinwang Mao, Ninghui Liang, Xinrong Liu, Zuliang Zhong, Chuanhua Zhou, Investigation on early-age cracking resistance of basalt-polypropylene fiber reinforced concrete in restrained ring tests, *Journal of Building Engineering*, 70 (2023) 106155
- [7]. H. Assaedi, F.U.A. Shaikh, I.M. Low, Effect of nano-clay on mechanical and thermal properties of geopolymer, *Journal of Asian Ceramic Societies*, 4 (2016) 19-28
- [8]. Zengzhi Sun, Qinwu Xu, Microscopic, physical and mechanical analysis of polypropylene fiber reinforced concrete, *Materials Science and Engineering: A*, 527, (2009) 198-204
- [9]. Kai Cui, Lihua Xu, Lijian Li, Yin Chi, Mechanical performance of steel-polypropylene hybrid fiber reinforced concrete subject to uniaxial constant-amplitude cyclic compression: Fatigue behavior and unified fatigue equation, *Composite Structures*, 311, (2023) 116795
- [10]. Tarek Aly, Jay G. Sanjayan, Factors contributing to early age shrinkage cracking of slag concretes subjected to 7-days moist curing; *Materials and Structures* 41(2008) 633–642
- [11]. S.R. Shashikumara, N. Pramukh, R. Abhishek, V.K. Nagaraj, Experimental study on the influence of polypropylene and steel fiber on flexural behaviours of high strength concrete beams, *Materials Today: Proceedings*, 2023, <https://doi.org/10.1016/j.matpr.2023.05.020>
- [12]. Chaojie Song, Gang Zhang, Zelei Lu, Xuyang Li, Xiaocui Zhao, Fire resistance tests on polypropylene-fiber-reinforced prestressed concrete box bridge girders, *Engineering Structures*, 282 (2023) 115800
- [13]. A.K. Devi K. Esakki, S. K. A. Dev, T. Gomathy, C. C. Gifita, Influence of adding steel – glass – polypropylene fibers on the strength and flexural behavior of hybrid fiber reinforced concrete, *Materials Today: Proceedings*, 2023, <https://doi.org/10.1016/j.matpr.2023.05.055>
- [14]. Ninghui Liang, Jinwang Mao, Ru Yan, Xinrong Liu, Xiaohan Zhou, Corrosion resistance of multiscale polypropylene fiber-reinforced concrete under sulfate attack, *Case Studies in Construction Materials*, 16, (2022) e01065
- [15]. Li Gong, Xingbo Yu, Yuting Liang, Xuelei Gong, Qiangye Du, Multi-scale deterioration and microstructure of polypropylene fiber concrete by salt freezing, *Case Studies in Construction Materials*, 18, (2023) e01762
- [16]. Wenmei Zhou, Jinxu Mo, Sheng Xiang, Lei Zeng, Impact of elevated temperatures on the mechanical properties and microstructure of waste rubber powder modified polypropylene fiber reinforced concrete, *Construction and Building Materials*, 392, (2023) 131982
- [17]. N. Sivakumar, G. Beulah Gnana Ananthi, M.S. Deepak, An evaluation study on amalgamation and performance of fiber reinforced concrete frames with infills and without in fills, *Materials Today: Proceedings*, 37, (2021) 2360-2367

- [18]. Zhenhua Duan, Qi Deng, Chaofeng Liang, Zhiming Ma, Huixia Wu, Upcycling of recycled plastic fiber for sustainable cementitious composites: A critical review and new perspective, *Cement and Concrete Composites*, 142, (2023) 105192
- [19]. Fang Xu, Chao Peng, Jing Zhu, Jianping Chen, Design and evaluation of polyester fiber and SBR latex compound-modified perlite mortar with rubber powder, *Construction and Building Materials*, 127, (2016) 751-761
- [20]. W.C. Tang, Y. Lo, A. Nadeem, Mechanical & drying shrinkage properties of structural-graded polystyrene aggregate concrete, *Cement & Concrete Comp*, 30 (2008) 403-409
- [21]. Hichem Berkak, Madani Bederina, Zoubir Makhloufi, Physico-mechanical and microstructural properties of an eco-friendly limestone mortar modified with styrene-polyacrylic latex, *Journal of Building Engineering*, 32, (2020)101463
- [22]. S. M. M. Sarmast, A. Kunte, & A. Roy, Synthesis, characterization and mechanical study of polypropylene polymer based reinforced concrete with different admixture. *Technium: Romanian Journal of Applied Sciences and Technology*, 4(7), (2022) 11–21
- [23]. Ankur C. Bhogayata, Narendra K. Arora, Workability, strength, and durability of concrete containing recycled plastic fibers and styrene-butadiene rubber latex, *Construction and Building Materials*, 180, (2018) 382-395
- [24]. Geok Wen Leong, Kim Hung Mo, Zhi Pin Loh, Zainah Ibrahim, Mechanical properties and drying shrinkage of lightweight cementitious composite incorporating perlite microspheres and polypropylene fibers, *Construction and Building Materials*, 246, (2020) 118410
- [25]. Manuel J. Chinchillas-Chinchillas, Víctor M. Orozco-Carmona, Alberto Gaxiola, Clemente G. Alvarado-Beltrán, Manuel J. Pellegrini-Cervantes, Francisco J. Baldenebro-López, Andrés Castro-Beltrán, Evaluation of the mechanical properties, durability and drying shrinkage of the mortar reinforced with polyacrylonitrile microfibers, *Construction and Building Materials*, 210, (2019) 32-39
- [26]. Ozkan Sengul, Senem Azizi, Filiz Karaosmanoglu, Mehmet Ali Tasdemir, Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete, *Energy and Buildings*, 43 (2011) 671-676
- [27]. Daniyar Akhmetov, Sungat Akhazhanov, Ainur Jetpisbayeva, Yuri Pukharenko, Yelena Root, Yelbek Utepov, Akbulat Akhmetov, Effect of low-modulus polypropylene fiber on physical and mechanical properties of self-compacting concrete, *Case Studies in Construction Materials*, 16 (2022) e00814
- [28]. Aashis S Roy, S Gupta, S Seethamraju, G Madras, P C Ramamurthy, Impedance spectroscopy of novel hybrid composite films of polyvinylbutyral (PVB)/functionalized mesoporous silica, *Composites: Part B Engineering* 58 (2014) 134–139
- [29]. Shaise K. John, Yashida Nadir, Alessio Cascardi, M. Muhammed Arif, K. Girija, Effect of addition of nanoclay and SBR latex on fly ash-slag geopolymer mortar, *Journal of Building Engineering*, 66 (2023) 105875

- [30]. Shafiq Ishak, Soumen Mandal, Han-Seung Lee, Dong-Eun Lee, Zhengxin Chen, Structure-property correlation of thermally activated nano-size phase change material in the cementitious system, *Journal of Building Engineering*, 66 (2023) 105871
- [31]. Xinxin Shi, Baokuan Ning, Jianping Liu, Zhisen Wei, Effects of re-dispersible latex powder-basalt fibers on the properties and pore structure of lightweight foamed concrete, *Journal of Building Engineering*, 75 (2023) 106984
- [32]. Sabireen, Faheem Butt, Afnan Ahmad, Kiffayat Ullah, Osama Zaid, Hammad Ahmed Shah, Tahseen Kamal, Mechanical performance of fiber-reinforced concrete and functionally graded concrete with natural and recycled aggregates, *Ain Shams Engineering Journal*, 14 (2023) 102121
- [33]. Chandra Sekhar Das, Tanish Dey, Ramkrishna Dandapat, Bibhuti Bhusan Mukharjee, Jitendra Kumar, Performance evaluation of polypropylene fibre reinforced recycled aggregate concrete, *Construction and Building Materials*, 189 (2018) 649-659
- [34]. Yibo Gao, Jianlin Luo, Shike Yuan, Jigang Zhang, Song Gao, Min Zhu, Zhiqing Li, Xiaoyang Zhou, Fabrication of graphene oxide/fiber reinforced polymer cement mortar with remarkable repair and bonding properties, *Journal of Materials Research and Technology*, 24 (2023) 9413-9433
- [35]. Joseph J. Assaad, Abdulkader El Mir, Durability of polymer-modified lightweight flowable concrete made using expanded polystyrene, *Construction and Building Materials*, 249, (2020) 118764
- [36]. Tumadhir Merawi Borhan, Rasha Jasim Al Karawi, Experimental investigations on polymer modified pervious concrete, *Case Studies in Construction Materials*, 12 (2020) e00335
- [37]. Ehab Hussein Bani-Hani, Mamdouh El Haj Assad, Maryam Al Mallahi, Zaid Almuqahwi, Md. Meraj, Md. Azhar, Overview of the effect of aggregates from recycled materials on thermal and physical properties of concrete, *Cleaner Materials*, 4 (2022) 100087
- [38]. Yuan Qin, Minghan Duan, Weili Ma, Yanlong Li, Heng Zhou, Yajun Lv, Ming Li, Experimental study on the damage permeability of polypropylene fiber-reinforced concrete, *Construction and Building Materials*, 286 (2021) 122592
- [39]. Eun-A Seo, Won-Woo Kim, Sung-Wook Kim, Hong-Kyu Kwon, Ho-Jae Lee, Mechanical properties of 3D printed concrete with coarse aggregates and polypropylene fiber in the air and underwater environment, *Construction and Building Materials*, 378 (2023) 131184
- [40]. Bijo MD, Sujatha Unnikrishnan, Mechanical strength and impact resistance of hybrid fiber reinforced concrete with coconut and polypropylene fibers, *Materials Today: Proceedings*, 65 (2022) 1873-1880