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A Review: Properties of Micro Steel Fibre (MSF) in High-Performance Concrete in Terms of Crack Propagation

Suchitra Ramasamy[1], Shahiron Shahidan[*2], Sharifah S.M. Zuki[3], Mohamad A.M. Azmi[4]

[1,2,3]Department of Civil Engineering, Faculty of Civil Engineering & Built Environment, University Tun Hussien Onn Malaysia, Parit Raja, 86400, Batu Pahat Johor, Malaysia.

[4]Department of Civil Engineering, Center for Diploma Studies, University Tun Hussien Onn Malaysia, 86400 Panchor, Johor, Malaysia.

[1]suchitraramasamy@gmail.com

[2*] shahiron@uthm.edu.my

[3] sharifahs@uthm.edu.my

[4]azim@uthm.edu.my

***Abstract* —** *High-performance concrete (HPC) applies to cement-based material with a strong capacity above 50MPa, has great ductility, and shows excellent performance. This paper reviews the properties of HPC, raw material, and cracking propagation. Reduction in porosity and improvement in microstructure increases the toughness of HPC. Natural materials such as supplementary cementitious material, aggregates, super-plasticizers, and micro steel fibers can enhance HPC's mechanical properties and workability. Also, the causes of cracking and relevant test for observing crack propagation are discussed in this paper. Thus, HPC manufacturing tends to improve over the years by using relevant raw materials, common technology such as conventional casting and room temperature curing, and related precautions to reduce cracking in concrete to prolong the service life of concrete structures.*

Keywords — *High-performance concrete, micro steel fibers, cracking.*

I. INTRODUCTION

Over the past three decades, high-performance concrete (HPC) has been widely used globally. The compressive strength of HPC ranges between 50 MPa to 100 MPa [10]. Besides, HPC is designed to produce more desirable workability and higher compressive strength than conventional concrete [18]. Based on its high compressive strength and great durability, HPC is mostly applied to high-rise buildings, bridges, offshores structures, harbor and coastal structures, underground constructions, and so on.

Generally, HPC mixtures have higher binders than conventional concrete, containing one or more additional materials (e.g., fly ash, silica fume, and granulated blast furnace slag) [14]. It is well known that a decrease in water-cement (w/c) ratio minimizes porosity and increases concrete strength while the addition of super-plasticizers increases concrete workability [35]. However, a low w/c ratio results in high self-desiccation, causing substantial autogenous shrinkage and an increase in early-age HPC's cracking potential under controlled conditions [34].

Adding discrete fibers into the concrete matrix helps reduce micro-cracking and restrain micro-cracking, along with improved post-cracking strength and ductility [38]. Steel fibers evenly distributed in a concrete matrix can hold the existing pore structures and prevent concrete from collapsing [40]. Nowadays, steel fibers are widely used to reinforce industrial floor slabs, standard reinforcing cages for tunnel segments, shotcrete, and prefabricated concrete products.

Many researchers have conducted studies on HPC, but information on HPC's materials and structural properties is still limited. This review includes the role of micro steel fibers (MSF) in overcoming cracking problems in HPC and the types of crack propagation that occur on the HPC surface.

II. HIGH-PERFORMANCE CONCRETE

The theoretical basis for producing HPC was originally developed in ceramic materials in the late 1950s and early 1960s. A single-phase polycrystalline ceramic materials showed that reduced particle dimension increases strength [17]. Neville and Aïtcin [29] stated that HPC is usually made of silica fume, fly ash, ground granulated blast furnace slag, or both materials. They also mentioned that the aggregates used to produce HPC should be 10 mm to 14 mm. Thus, with a smaller maximum size, the differential stresses at the aggregate-cement paste interface, which could lead to micro-cracking, are smaller. Moreover, smaller aggregate particles are stronger than large particles. Thus, a reduction in coarse aggregates can potentially remove the largest flaws which control strength.

Supplementary cementitious materials (SCMs) as part of binders for concrete have been developing to produce high strength and high-performance concrete. A study done by Chang *et al.* [7] on the design considerations for HPC durability in the beam shows that HPC contains pozzolanic materials, smaller voids, and a higher impedance resistivity coefficient demonstrated improved durability. Besides, the presence of steel fiber reduces the crack width to less than 0.3 mm. This proves that HPC has better resistance towards corrosion. However, Weber and Reinhardt [41] stated that HPC's strength is drier curing conditions (autogenous curing). The drier the curing condition, the higher the measured compressive strength. Therefore, wet curing can be neglected as it does not influence compressive strength.

Weber and Reinhardt [41] found that smaller pores are caused by continuous hydration from the study. Additional C-S-H grows into pores, separates the pores into smaller pores. As a result, higher compressive strength is obtained. Researchers found that the use of Portland cement blended with ultrafine ground granulated blast furnace slag (GGBS) and silica fume (SF) results in HPC of good workability. For instance, Chang [8] revealed that a mix design containing GGBS and SF has an initial slump of 225 mm, reducing to 250 mm after 45 minutes. Therefore, the slump height falls within the range of 230 mm – 270 mm. This proves that the HPC made of blended Cement possesses good workability.

Nonetheless, the use of ultrafine GGBS and SF can significantly minimize cracking and drying shrinkage [19]. In particular, concrete mix design with low water-binder (w/b) ratios that include highly active pozzolans such as SF has indeed been observed to undergo significant cracking of shrinkage, particularly if there is no sufficient curing [15]. This tendency for increased cracking of shrinkage in these types of mixtures can be primarily due to an increase in autogenous and drying shrinkage, as well as reduction of creep.

The most important concrete characteristics are w/c and w/b ratios as they influence its properties in fresh and hardened states and its durability. The initial mechanical properties are primarily related to the w/c ratio since the first hydrates that give the Cement paste its strength are the ones that form on the cement particle surface. Meanwhile, the w/b ratio has a long-term effect on the compressive strength and durability of cement pastes manufactured with blended Cement containing supplementary cementitious materials [2]. To prove the statement of Aïtcin [1], research carried out by Rao and Sekhar [32] reported that the lower the w/c and w/b ratios, the higher the strength of concrete made from a high volume of fly ash.

Next, to produce HPC, an additive should be included to improve its workability. For example, a super-plasticizer (SP) is a common additive used in the production of HPC. Most researchers choose to add at least 1 % to 2 % of binder content. As the specific surface of ultrafine GGBS and SF is higher than that of cement particles, a greater SP must achieve good rheological properties [43]. The mix design, raw materials, w/c ratio, w/b ratio, steel fibers, and SP are the most important factors in HPC production.

Over the years, HPC had gone through a lot of revolution and achieved a new record in strength, durability, and workability. Thus, a new term has been given to HPC, namely Ultra-High Performance Concrete (UHPC). The production of UHPC is almost the same as HPC. The only difference between UHPC and HPC is the compressive strength of the concrete. HPC's compressive strength ranges between 50 MPa and 150 MPa [37], while the compressive strength of UHPC ranges between 150 MPa and 810 MPa [39]. The application of HPC and UHPC to building structures increases the service life and contributes to sustainable construction materials [17].

III. RAW MATERIALS

A. *Cementitious Materials*

Cementitious material acts as a binder to bind coarse and fine aggregates to form concrete composites. Pure Portland cement is known as a type of traditional cementitious material. On the other hand, silica fume (SF), fly ash (FA), and ground granulated blast furnace slag (GGBFS) are known as supplementary cementitious materials (SCMs). Table 1 shows the chemical composition (%) and the properties of SCMs. The production of pure Portland cement emits carbon dioxide to the surroundings, which may be harmful to the environment. Due to reserving raw materials for future usage, cementitious materials using industrial waste have been carried out. Researchers have developed a cement composite where Portland cement was partially replaced with industrial and agricultural wastes. Through these processes, the term "Blended Portland Cement" was created [30].

TABLE 1: Chemical composition (%) and the properties of binding materials [18]

Binder	Chemical Composition (%)					Average Particle Size (μm)
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	
Cement	19.95	4.71	60.58	1.41	2.90	≈ 40
GGBS	34.35	15.26	36.80	9.10	1.40	2.5
SF	91.25	0.47	0.43	0.93	0.91	0.2

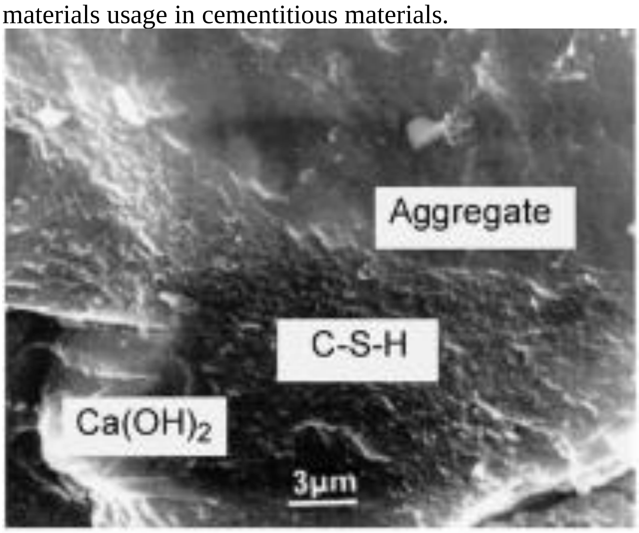
SCMs are widely used as pozzolanic materials in HPC to improve their long term durability. It is well known that pozzolanic concrete contributes to compressive strength in two ways: the filler effect and the pozzolanic reactions [5]. A study carried out by Elahi *et al*. [13] proved that the partial replacement of Portland Cement with 15% of SF in a cement composite could achieve a compressive strength of 120.8 MPa curing period of 28 days. From this study, Elahi *et al.* [13] confirmed that particle size and surface play an important role in the rate of reactivity. Consequently, SF's hydration rate is higher than the GGBS'. As a result, SF can contribute to the production of strength in hydration at an early stage compared to GGBS.

Yang *et al*. [42] substituted 3 to 40% of SF, 3 to 70% of Class F FA, and 3 to 80% of GGBS into ordinary Portland cement (OPC). The different ranges of compressive strength obtained through laboratory testing were: 7-170 MPa for OPC mixtures, 7-100 MPa for OPC with FA mixtures, 7-140 MPa for OPC with GGBS mixtures, 7-170 MPa for OPC with SF mixtures, and 40-170 MPa for OPC combined with GGBS and SF mixtures. From the study, Yang *et al*. [42] agreed that an increase in compressive strength of concrete commonly follows the consumption of a greater amount of binder because higher strength requires a lower water-to binder ratio.

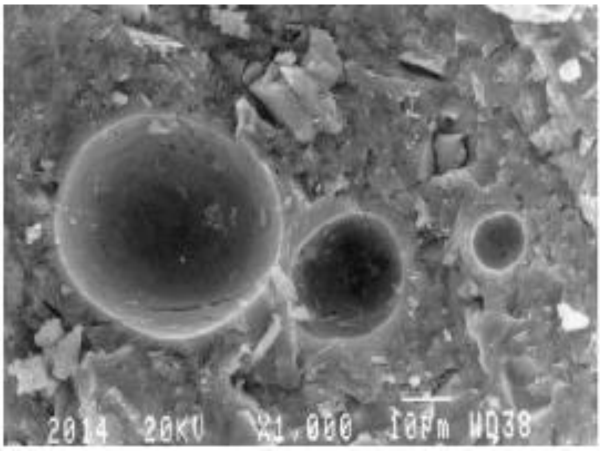
In contrast, higher concrete strength contributes to a decrease in CO_2 emissions as only a smaller OPC is required. The hydration of cementitious materials in HPC is similar to ordinary Cement (OC). First, the Portland cement hydrates to form calcium silicate hydrate and calcium hydroxide, then mineral admixtures such as SF and FA react with calcium hydroxide to form calcium silicate hydrate (C-S-H) [39]. The hydration mechanism can be observed by recording the heat evolution rate and the total heat emitted by the pastes. According to McCarthy and Dyer [27], the total heat released from blended Cement in the first 2 days is always lower than Portland cement. Still, it is generally, the total heat released is higher than the normal Portland cement pastes.

As mentioned above, the addition of SCMs in concrete affects the long term durability of HPC. The inclusion of Metakaolin (MK) in concrete may improve the pore microstructures, which results in a reduction in initial surface absorption and sorptivity. This is due to the pozzolanic reaction, which consumes the free calcium hydroxide created by Cement's hydration, resulting in C-S-H's dense production [21]. Fig 1 shows HPC's microstructure with low porosity and the matrix's homogeneity. The absence of a transition zone between the aggregate and Cement and dense cement paste in an air-entrained HPC. However, MK is not resistant to chloride attack. Therefore, a study done by Madandoust *et al*. [26] stated that a higher content of rice husk ash (RHA) in concrete decreases the penetration of chloride into concrete specimens. SCMs in concrete with reactive aggregates decrease or even stop expanding the concrete matrix due to alkali-silica reaction.

Thus, the inclusion of SCMs into "Pure" Portland cement can reduce the emission of CO_2. At the same time, it improves the compressive strength of the concrete specimens and their durability. Moreover, the fineness of SCMs particles may reduce the microstructure of concrete specimens. As a result, partial replacement may result in sustainable building materials that may reduce raw materials usage in cementitious materials.



(a) Absence of transition zone between the aggregates and cement paste



(b) Dense cement paste in air-entrained high-performance concrete.

Fig 1: Microstructure of HPC – low porosity and homogeneity of the matrix [1].

B. Aggregates

In conventional concrete, aggregates have higher stiffness than cement paste, and they also act as a skeleton. Natural fine aggregates that are usually used include river sands that mainly contain silicates to achieve higher compaction. Meanwhile, natural coarse aggregates such as rounded river gravel (siliceous composition) and crushed dolomitic coarse aggregates improve concrete workability and mechanical behavior.

Al-Jabri *et al*. [3] used copper slag as a sand replacement in HPC. They found that the addition of up to 50% of copper slag as sand replacement yielded comparable strength with that of the control mix, that is, 77.8 MPa and 76.9 MPa, respectively. However, a study carried out by Chithra *et al*. [10] proved that nano-silica cement mortar cubes containing 40% copper slag as fine aggregate replacement recorded an increase in compressive strength. Apart from that, coarse aggregates can be replaced with other industrial waste.

For instance, a study done by Faleschini *et al*. [14] made use of electric arc furnace slag (EAF) to replace the coarse aggregates in HPC partially. The size of coarse aggregates and EAF used ranges between 4 mm – 16 mm. the results of this study showed that the highest compressive strength obtained by conventional concrete is 56.39 MPa. In contrast, the compressive strength of 76.43 MPa was obtained for a concrete specimen that contained EAF as a partial replacement of coarse aggregates. Moreover, concrete specimens that consist of EAF as coarse aggregate improves the resistance towards chloride penetration.

To reduce the usage of raw aggregates from quarries, recycled concrete aggregates (RCA) from demolished structures have been used to replace HPC manufacturing aggregates. A related study was conducted by Gonzalez-Corominas and Etxeberria [18] to determine the effects of using RCA on the shrinkage of HPC. As a result, a higher plastic and drying shrinkage is obtained when RCA's consistency decreases and the replacement ratio increases. Nevertheless, the use of a higher content of lower – quality

RCA has proven to reduce autogenous shrinkage and function as an internal curing agent.

Overall, the size and type of aggregates are important in the production of HPC. From previous studies, it can be concluded that the interfacial transition zone (ITZ) between aggregates and a matrix should be compact with low porosity to produce high-quality HPC. Therefore, the selection of both coarse and fine aggregates is very important in the manufacturing of HPC.

C. Superplasticizers

Superplasticizers (SPs) are water-reducing admixtures but are substantially and distinctly more effective than common water-reducing admixtures. SPs are also typically highly distinctive, making it possible to manufacture concrete that is significantly different in its fresh or harden state from concrete manufactured using water-reducing admixtures of Type A., D, or E since very low w/c or high workability can be achieved. In ASTM terminology, SPs are referred to as Type F admixtures. When the SPs are retarding, it is also known as a Type G admixtures.

SPs are generally made up of soluble organic polymers composed of synthetic chemicals. They are used to optimize concrete workability without reducing the amount of water or increasing concrete strength. Some SPs contain calcium salts that are comparatively less soluble than sodium salted SPs. SPs can be categorized into four groups, namely Lignosulphonate, Sulphonated Naphthalene Formaldehyde (SNF) Condensate, Sulphonated Melamine Formaldehyde (SMF) Condensates, and Polycarboxylates. Melamine and Naphthalene-based SPs are commonly used [33].

According to Li *et al*. [24] on the effect of PCE-type SP on the early-age behavior of UHPC, it was demonstrated that the saturation dosage exists and alkene is the key factor of control on the dispersing efficiency of PCE-type SP. Therefore, the dispersing ability of PCE-type SP is highly dependent on its chemical structures and particle adsorption efficiency. Paste flowability consistently increases from critical dosage to saturation dosage and remains constant after achieving maximum surface coverage of particles above the saturation dosage.

SPs usually reduce bleeding tendency in fresh concrete by reducing the w/c ratio and water content in concrete. However, SPs can prolong the setting time of concrete as more water is available to lubricate the mixture. In harden concrete, SPs increases compressive strength by enhancing the effectiveness of compaction to produce denser concrete. Retaining the concrete in liquid stated for longer periods could reduce the risk of drying shrinkage. Moreover, SPs' presence in concrete slows down the carbonation rate as the w/c ratio is reduced [4].

D. Micro Steel Fibres

Steel fiber reinforced concrete is one of the innovative new construction materials. Uniformly dispersed steel fibers of various shapes and geometries in a cement matrix can be used to solve crack tolerance and brittleness of cement composites [25]. Due to its higher flexural strength, better tensile strength and modulus of rupture, higher shear strength, higher shock resistance, better ductility, fatigue resistance, crack resistance and failure toughness, and steel fibers in the production of HPC [6]. Fig 2 shows an image of double hooked-end steel fibers.

According to Kayali [22], fibers' contribution is negligible at the normal application rate of about 1% per concrete volume, where their function is confined only to crack bridging. Fig 3 shows the image of steel fiber reinforced concrete. As a result, steel fiber concrete is increasingly being used in structures such as airport pavements, bridge decks, machine foundations, blast resistance structures, piles, pipes, sea protective structures, hip-hulls, and storage tanks.

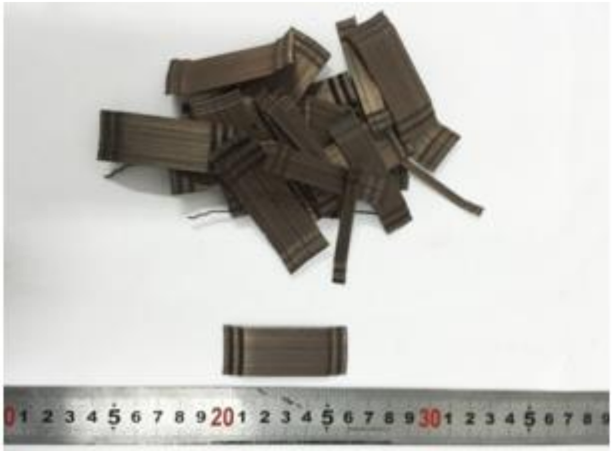


Fig 2: Photograph of double hooked-end steel fibers [34].

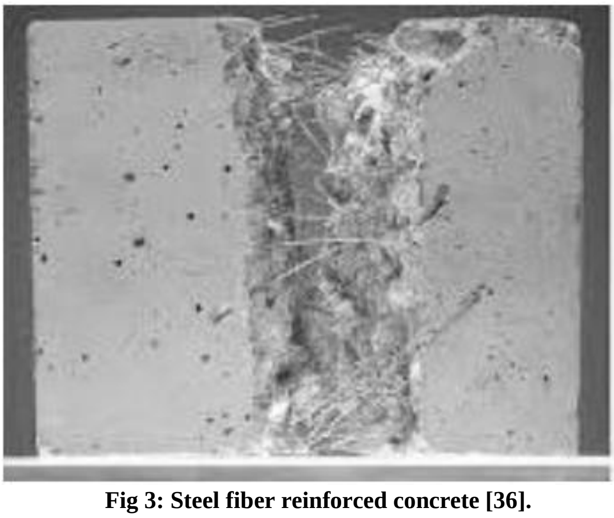


Fig 3: Steel fiber reinforced concrete [36].

IV. CRACKING

Cracking that occurs in fresh concrete can be categorized as plastic shrinkage cracking and plastic settlement cracking. Fig 4 shows plastic shrinkage cracks appearing on the concrete surface a few hours after placement. Meanwhile, the cracks in hardened concrete are caused by drying shrinkage or restrained early-age thermal movements [23]. Overloading, in comparison to the actual strength of the concrete element, may also cause cracking.

Fig 4: Plastic shrinkage cracks appearing on the concrete surface a few hours after placement [16].

According to Shweta and Kavilkar [36], structural cracks (microcracks) develop even before loading, particularly due to drying shrinkage or other volume change causes. However, the initial cracks seldom exceed a few microns in width. Nataraja stated that when loads are applied, microcracks propagate and open up due to stress concentration, causing additional microcracks to form. Thus, microcracks are the main cause of elastic deformation in concrete.

In brittle materials, crack propagation is the main cause of material failure. Cracks in early-age concrete tend to propagate by opening along their axes and are often essentially planar over significant distance relative to the crack's depth. There are three basic cracking modes: tensile opening, in-plane shear, and anti-plane shear [11]. Fig 5 shows the basic modes of cracking.

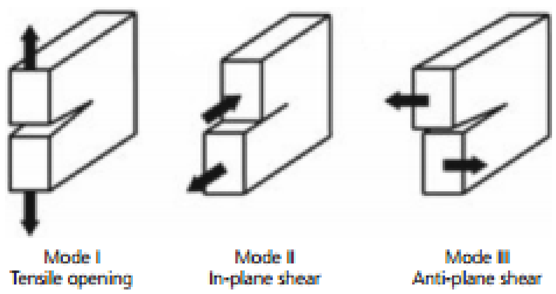


Fig 5: The basic modes of cracking [11].

To understand more about the relationship between crack speed (CS) and load rates, a study on CS in UHPC was examined by Pyo *et al.* [31] using notched three-point bending specifications through the use of cement composite mixed with 0%, 0.5%, and 1.00% of steel fiber volume. The outcome of this study is shown in Fig ^. From the observation on Fig 6, CS-0% reveals brittle failure without a substantial weakening region and therefore exhibits rapid crack speed even at weak load rates. Besides, comparing CS-0.5% and CS-1.00% momentarily displays more ductile failure patterns, enabling massive energy dispersion resulting in relatively slow crack speeds under the low load speed regime.

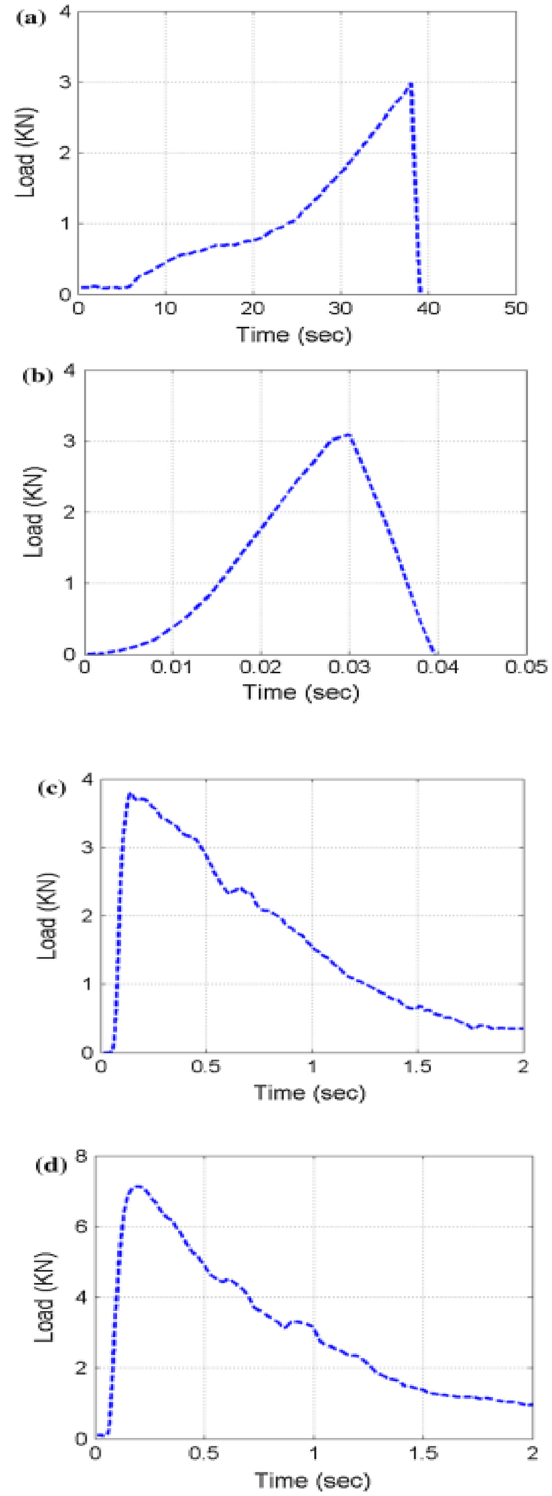


Fig 6: Examples of load curves for the slow loading cases: (a) CS-0% tested at 0.0076 mm/s; (b) CS-0% tested at 7.6 mm/s; (c) CS-0.5% tested at 7.6 mm/s; (d) CS-1.00% tested at 7.6 mm/s [31].

A study was done by Reddy and Subramaniam [9] using two different types of fibers, that is, FibreTuff monofilament macro-polypropylene fibers (SPFR) and polyolefin-based macro-synthetic bi-component fibers, reveals the results as shown in Fig 7. It has been shown that with a modest increase in crack tip opening displacement (CTOD), there was initially a very rapid increase in crack depth in all the specimens. The crack depth for a given CTOD obtained from the fiber-reinforced concretes (FRC) specimens were nominally identical to that of the control specimens. The part where the CTOD increased without a significant increment in crack depth is directly related to the hinge opening.

Within the 0.15 mm – 0.20 mm CTOD range, the crack developed to almost 90% of the beam's depth, and then the crack opened by hinging. The FRC specimens display strong hinging behavior and wider surface crack opening displacement values. As a result, macro-synthetic fiber reinforced concrete reveals that the addition of macro-synthetic fibers up to 8 kg/m^3 (0.9% by volume) did not significantly influence crack propagation but provide resistance to the opening of the hinge.

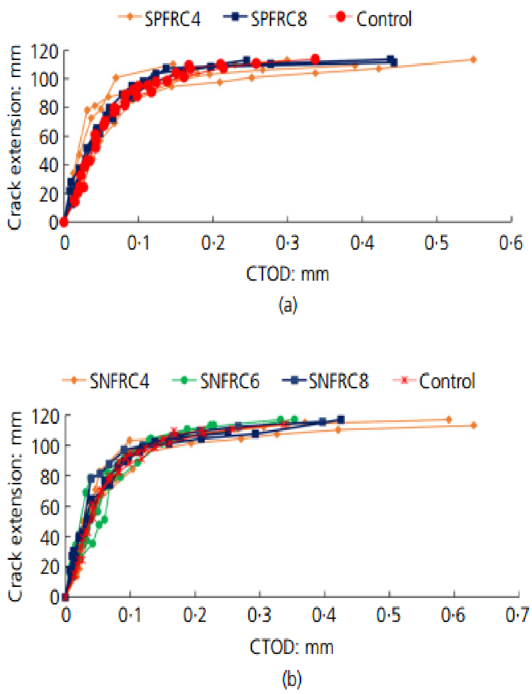


Fig 7: Depth of crack with CTOD (a) SPFRC beams and (b) SNFRC beams [9].

Restrained shrinkage cracks often occur in concrete components and structures with a high area-to-volume ratio. This includes factory floors, concrete pavements, and bridge decks. On the same note, Dong *et al.* [12] researched crack initiation and crack propagation of concrete through a restrained shrinkage circular ring test. The results showed that the initial cracking ages predicted by a numerical model agreed with the analytical results. Once initiated, the cracks spread consistently. However, the study also mentioned that crack propagation also depends on the degrees of restraint caused by steel and concrete properties and ring specimens' geometry.

Cracking may occur when the residual tensile stress is higher than the tensile strength [20]. From previous studies, it is clear that steel fibers can effectively reduce shrinkage and cracking potential. For example, a study was done by Shen *et al.* [34] utilized double-hooked end steel fibers to observe high-strength concrete's cracking potential (HSC). From this study, Shen *et al.* [34] found that the steel ring strain declined with double-hooked-end steel fibers' increment quantities. In contrast, residual stress or relaxed stress fluctuates with the increasing amount of double hooked-end steel fibers.

From Fig 8, it can be concluded that at the age of 21.25 days, which is approximate 22 days after casting, the maximum residual stress values of concrete ring specimens recorded were 3.17 MPa, 2.38 MPa, 2.07 MPa, and 1.62 MPa, respectively, when the quantities of double hooked-end steel fibers increased from 0% to 0.36% in the concrete specimens. These outcomes prove that as the quantities of steel fibers increases, the residual stress decreases.

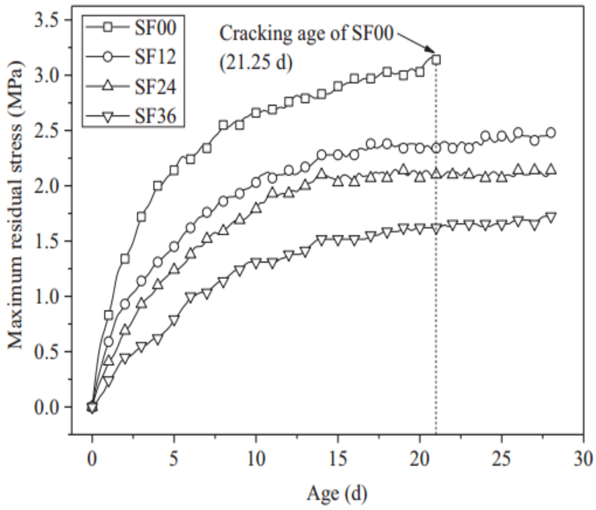
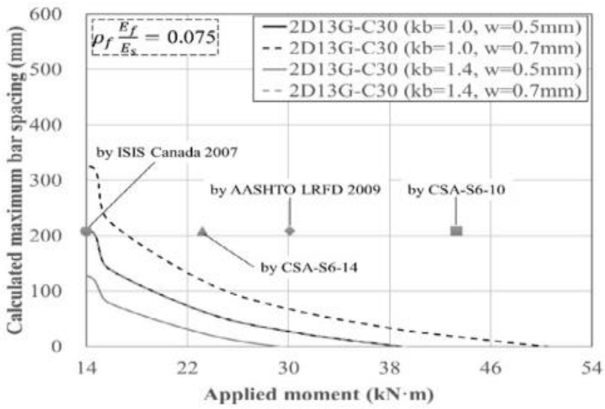


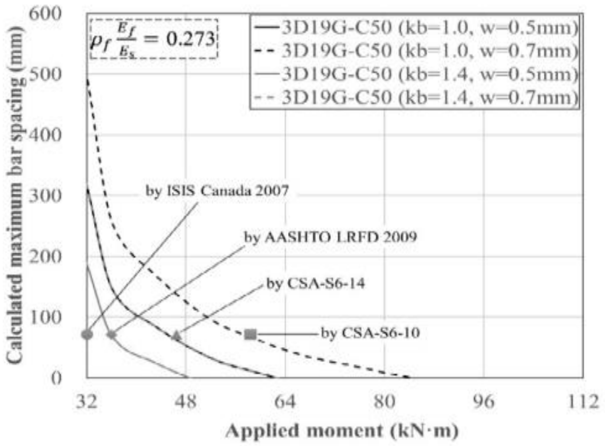
Fig 8: Relationship between maximum residual stress in concrete ring specimens and age [34].

Fiber-reinforced polymer (FRP) bars have a lower modulus of elasticity and no ductility like steel bars. The lower elasticity modulus of the FRP bars causes issues of serviceability such as crack widths and deflections. Therefore, the assessment of serviceability in cracking was indeed an important problem for reinforced concrete members of FRP due to the low flexural stiffness of the FRP bars, resulting in rather substantial flexural deflection. Based on the statement above, a study on cracking control comparison in the specifications of serviceability in cracking for FRP reinforced concrete beam was carried out by Ju *et al.* [20]. In this study, the researcher used four different serviceability specifications, which is based on the tensile strain of reinforcement for ISIS Canada 2007; allowable deflection for AASHTO 2009; compressive concrete strain for CSA-S6-10; and stress limit of glass bar reinforced polymer (GFRP) bar for CSA-S6-14, to determine the level of application for the serviceability in cracking.

As shown in Fig 9, it illustrates the bar spacing of two experimental cases at the serviceable moment corresponding to the four serviceability specifications as mentioned above. The four dots that were plotted in each graph represents the results obtained from the four specifications, as stated above. For the specimens 2D13-C30, only the serviceability in cracking of the ISIS Canada 2007 fulfilled the bar spacing corresponded to the serviceable moment, with a low equivalent reinforced ratio. The specimen 3D19G-C50 with the highest equivalent ratio of 0.273 showed a sufficient spacing margin for the ISIS Canada 2007 and the AASHTO LRFD 2009 specifications. As a result, the four serviceability specifications may contribute different serviceability in the cracking of FRP concrete structures.



(a) 2D13G-C30



(b) 3D19G-C50

Fig 9: Maximum bar spacing and applied moment relationship by comparing the serviceability specifications [20].

Moreover, fiber reinforced concrete (FRC) is a composite material characterized by an increment in the post-cracking tensile residual strength. It is also known as toughness because the fiber reinforcement mechanism provided by fibers merge the crack surfaces. To comply with the statement, a study done by Sprince *et al*. [37] using polyvinyl alcohol (PVA) fibers to produce two different high-performance fiber reinforced cement composites (HPFRCC) that consist of micro-silica (SF) and nano-silica (NN. Fig 10 portrayed the fibers' performance towards the experimental loads and the readings obtained from the crack mouth opening displacement (CMOD).

As displayed in Fig 10, the experimental findings are very identical. They indicate that NN has no major effect on the tensile load and the CMOD properties of fiber-reinforced HPC properties. The average tensile load for NN specimens was 570 N, and the reading on CMOD was 0.57 mm. On the other hand, the tensile load for SF specimens was 613 N, and the CMOD reading obtains 0.59 mm, respectively.

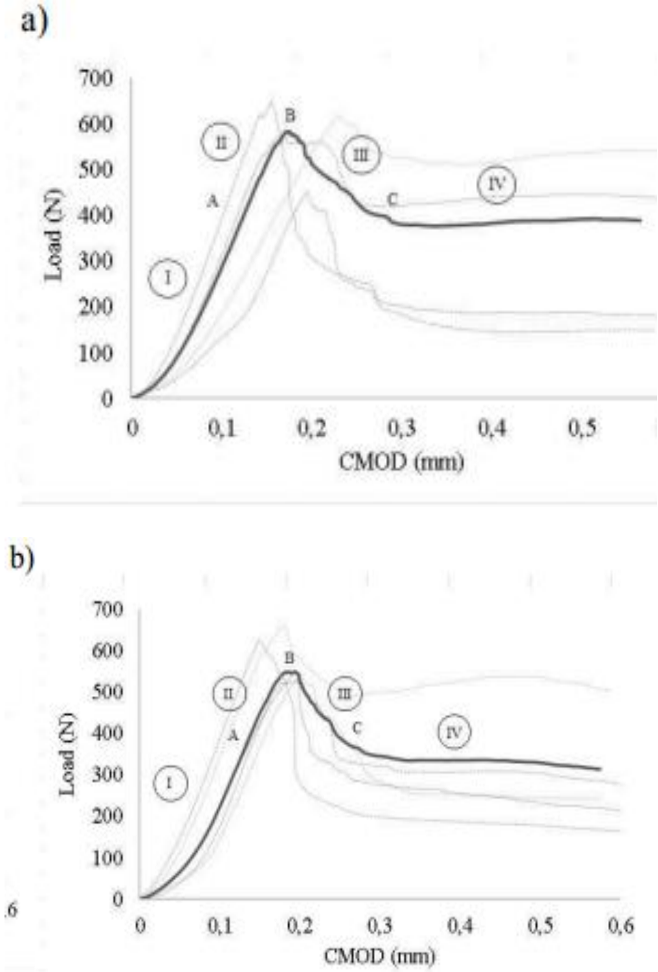


Fig 10: Load – CMOD curves measured during testing (a) for SF specimens; (b) for NN specimens [37].

Overall, the crack initiation in a concrete matrix is due to the drying shrinkage of concrete. This phenomenon can be reduced by using an appropriate w/c ratio and suitable admixtures. To control cracks from propagating further, steel fibers will act as a bridging element to reduce crack width in a concrete matrix.

V. CONCLUSION

This paper presents an overview of micro steel fibers (MSF) properties in HPC in cracking. The manufacturing of HPC is highly dependable on the selection of raw materials. To enhance the concrete matrix's mechanical properties, the interfacial transition zone (ITZ) should be rigid. To achieve a less porous microstructure in a concrete specimen, the application of finer SCMs is necessary. This is because SCMs fill up spaces in concrete specimens and increase the concrete's compressive strength. Apart from that, the initiation of cracks and crack propagation can be mitigated through the application of steel fibers. The widely dispersed steel fibers in the concrete matrix act as a bridging element between the crack's width. Moreover, the steel fibers can withstand high tensile pressure, which will prolong the service life of concrete structures.

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