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Static and dynamic properties of concrete with different types and shapes of fibrous reinforcement

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HIGHLIGHTS

- Concrete are reinforced with different types and shapes of fibres.
- Split Hopkinson Pressure Bar (SHPB) is used to study the dynamic properties of the FRC.
- W-shape steel FRC shows the superior static and dynamic behaviours.
- PP fibres slightly reduce the static, but improve the dynamic properties of concrete.
- 5% coir fibre had enhanced concrete dynamic stress, at par with W-shape steel fibre.

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ABSTRACT

This research determines the static compressive, split tensile and flexural strengths as well as dynamic stress, strain and toughness of fibre-reinforced concrete (FRC) at strain rates of 30–50 s^{-1} (single impact pressures of 2 and 3 MPa). Three fibre types (steel, polypropylene (PP) and coir (CF)) with different shapes, sizes, lengths and contents are considered. The newly modified W shape steel fibre has the greatest influence on concrete static and dynamic properties. PP fibre slightly reduces the concrete mechanical properties, but improves the dynamic properties 15% more compared to plain concrete (PC). The compressive strength of 5% CF concrete is slightly improved, but the flexural and split tensile strengths are improved by 11% and 35%, respectively, compared to PC. There are significant improvements in dynamic stress, strain and toughness due to addition of 5% CF in concrete. CF stands at par with steel fibre in enhancing both the static and dynamic properties of FRC.

1. Introduction

Concrete structures may be exposed to loading within short time periods such as earthquakes, impacts and explosions during their service lives. Concrete responds differently to dynamic loading compared to static loading. Plain (unreinforced) concrete (PC) has high compressive strength but poor tensile strength (at approximately one tenth of its compressive strength) and low resistance to tensile cracking due its brittle characteristic. For this reason, the strain capacity of PC is inadequate for absorbing energy and resisting impact loads. Concrete structures must be designed to resist dynamic loads by improving the material's capacity to absorb shock energy. The brittle characteristics of concrete members can be ameliorated by adding fibres. When added to the concrete mix as reinforcements, fibres have the potential to increase the bond of the Portland cement paste and the concrete matrix and improve the mechanical properties. The primary role of fibre in a concrete mix is to reduce and control the speed of tensile cracking propagation by keeping the crack widths to a minimum. By adding fibres into a concrete mix, unstable tensile crack propagation is transformed to a slow, controlled crack growth. Therefore, the inclusion of fibres in concrete reduces the acceleration of shear and flexural crack propagation. Furthermore, the addition of fibre enhances the ductility of the concrete and thereby improves its energy absorption capacity. Additionally, fibre can provide better resistance to high strain rate loadings compared to PC. The tensile and compressive stresses of fibre reinforced concrete (FRC) are enhanced more than PC when loaded at high strain rates.

Fibre reinforcements such as horsehair and straw in mortar and sun-dried adobe bricks have been used in building materials for centuries [1]. Currently, many fibre types such as steel, synthetic, glass and natural fibres are specifically designed and manufactured for structural development purposes. Natural reinforcing materials

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can be obtained at low cost and with low levels of energy consumption by using local manpower and technology. The utilisation of natural fibre as a form of concrete reinforcement is of particular interest in less-developed regions where conventional construction materials are not readily available or expensive.

Vajje and Murthy [2] used different types of natural organic fibres, including jute, sisal, hemp, banana and pineapple, in order to study the properties of concrete. They concluded that the inclusion of natural organic fibres may have improved some concrete properties and reduced others, as each fibre exhibited its own unique properties. However, Sivaraja et al. [3] found that the addition of natural fibres (coir and sugarcane) enhanced the compressive, split tensile and flexural performance of concrete. Ramakrishna and Sundararajan [4] prepared slabs reinforced with coconut, sisal, jute and hibiscus cannabinus (kenaf) fibres in order to test impact resistance. They reported that a coconut fibre content of 2% and a fibre length of 40 mm demonstrated the best performance by absorbing 253.5 J of impact energy. They also mentioned that at ultimate failure, all fibres (except coconut fibres) exhibited fibre fracture, whereas coconut fibre showed fibre pull-out. Agopyan et al. [5] used both coir and sisal fibres as replacements for asbestos in roofing tiles and performed a three-point bend test. Their test results showed that the maximum load endured by the coir tiles was much higher than the sisal tiles. Therefore, coconut fibre is considered the most useful and inexpensive type of natural fibre for use in concrete composites. Significant research on coir fibre-reinforced concrete (CFRC) already exists, and it is generally accepted that the optimum content of coir fibre varies as the source of coir fibre changes. The optimum coir fibre content, by mass of cement, obtained by previous studies ranges between 0.5% and 5%.

The static properties of CFRC have been studied by numerous researchers. It has been determined that the flexural strength of CFRC is much greater than that of PC [6–8]. In contrast, Ali et al. [9] found that the modulus of rupture (MOR) for PC beams is typically higher than those of CFRC beams. According to their study, the MOR of CFRC with 5% fibre content and 5-cm fibres slightly increased to 4% when compared to PC. In addition, the split tensile strength of CFRC significantly increased [8–10]. The compressive strength of CFRC has been determined in numerous existing studies. Some researchers have reported that the compressive strength of CFRC has increased from 11% to 24% [8,9]. However, some researchers reported on the negative influence of coir on the compressive strength of CFRC [10,11].

The dynamic properties of CFRC have also been studied by various researchers. Coir fibres were used by Cook et al. [12] as reinforcement in low-cost roofs. They measured the impact resistance of coir fibre-reinforced cement roofs by dropping a 50-mm diameter 0.53 kg steel ball onto the centre of the sample. They found that the impact index of the coir fibre-reinforced cement roofs increased with increase in fibre volume and length. Similarly, a drop-weight impact test was conducted by Ali et al. [9] in order to evaluate the damping ratio and fundamental frequency of coir fibre-reinforced beams. According to their test results, a higher coir fibre content led to increased damping; however, the static and dynamic elastic modulus decreased. They concluded that the optimum coir fibre length and content were 5 cm and 5% by mass of cement, respectively. More recently, Wang and Chouw [13] carried out a study to investigate the behaviour of CFRC under impact loading. The coir fibre used in their study was 5 cm in length, and the coir fibre content was 0.4% by total weight of the concrete mix. A comparison between the PC and CFRC impact behaviours was reported in their study. Based on their results, the energy absorption capacity of CFRC was much higher than that of PC. It was also observed that the impact behaviour of PC featured brittle failure, whereas the tested CFRC specimens exhibited ductile failure with small cracks.

Significant research has also been carried out regarding fibre-reinforced concrete (FRC) using steel, polyvinyl alcohol (PVA) and polypropylene (PP). In recent decades, the application of steel fibre-reinforced concrete (SFRC) has consistently increased due to its significantly improved properties. It is currently applied in airport and highway pavement, earthquake and impact-resistant structures, tunnels, bridges and hydraulic structures [14]. A significant literature related to the FRC is discussed comprehensively in the "State-of-the-Art Report on Fiber Reinforced Concrete" published by ACI committee 544. According to this article the behaviour of FRC depends on number of factors [15]. Erdogmus, 2015 [16] categorized those factors as base matrix characteristics, fibre characteristics and composite mixture characteristics.

Tan et al. [17] reported compressive and flexural strength increases of up to 30% through the addition of steel fibre. According to Nagarkar et al. [18], the compressive, split tensile and flexural strengths of steel fibrous concrete increased by up to 13–40% when steel fibres are added at different aspect ratios and volume fractions. In addition, the inclusion of steel or PVA fibres in concrete significantly increases other properties such as stress–strain resistance, impact resistance, resistance to flexural fatigue and ductility [7,19–22]. It was observed that the addition of steel fibres increased the increment of compressive and split tensile strength of concrete by up to 30%, whereas the addition of PP fibres only increased these tensile strength increments by 4% compared with PC fibres [23]. Aliabdo et al. [19] also found that specimens reinforced with steel fibres showed considerably better behaviour when compared to specimens reinforced with PP fibres. The static and dynamic properties of concrete reinforced with coir, steel, PVA and PP, as obtained from existing literature, are presented in Tables 1 and 2.

Some researchers have added mineral admixtures such as fly ash (FA), silica fume (SF) and metakaoline to the FRC in order to enhance the mechanical properties of FRC. The optimal portion of silica fume (SF) is approximately 5% for improving the mechanical properties [24,25], and the concrete strengths increased significantly with the fibre content and SF addition [26,27].

A review of the above studies shows that only a few studies investigated the dynamic properties of CFRC. It should also be noted that a Split Hopkinson Pressure Bar (SHPB) apparatus was not used to investigate the dynamic properties of CFRC. Therefore, this study uses a SHPB to investigate the dynamic properties of CFRC with different contents of coir fibre. However, the crucial factor of FRC is impact resistance, and numerous experiments have been previously conducted using various fibre shapes and material types with different equipment [28]. The impact load is generated by either sticker bar impinging in an SPHB test [17,20,21,29–31] or dropping weights [1,32–34]. In this study, three different shapes of steel fibre types i.e., Hook-Ended Steel Fibre (HKSF), Proposed Steel Fibre I (γ-shape) (PSFI), Proposed Steel Fibre II (W-shape) (PSFII), and two types of PP fibre (PPI & PPII) were also considered to study the dynamic and static properties of FRC (reinforced with steel and PP). Namaan introduced steel fibres having a tri-dimensional configuration for use as reinforcement for Portland cement concrete matrices in his patent article **US 3852930 A** [35]. Namaan and co-workers had conducted vast researches in order to investigate the various properties of FRC using Hook-Ended Steel Fibre and also other shapes [36–38]. Namaan, 2003 also proposed newly developed twisted fibres named as torex fibres with their several advantages in cement matrices [39]. In present study, the two types steel fibres are modified based on gap of the previous studies. Studies and results on other fibre types have not been as extensive or as conclusive as those on steel fibres.