Construction and Building Materials 182 (2018) 94–107

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Contribution of plant fibers in improving the behavior and capacity of reinforced concrete for structural applications

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HIGHLIGHTS

- Contribution of plant fibers in altering behavior of reinforced concrete (RC) is evaluated.
- Wheat straw in concrete having varying flexure and shear rebars are considered.
- To start with, practical implications of concrete pavements are taken into account.
- Wheat straw in RC delayed crack initiation and enhanced its load capacity (up to 7.5%).
- Concrete pavement with wheat straw can yield comparable design and better behavior.

ARTICLE INFO

Article history:
Received 17 February 2018
Received in revised form 12 May 2018
Accepted 5 June 2018

Keywords:
Wheat straw
Natural fibres
Wheat straw reinforced concrete
Natural fibre reinforced concrete with steel rebars

ABSTRACT

Plant fibers (especially, wheat straw) are available surplus to requirements in sub-tropical regions. Many researchers have studied these fibers for non-structural applications. However, for civil engineering structural applications, in depth behavior of wheat straw reinforced concrete (WSRC) with steel rebars is not known. For this purpose, WSRC needs to be explored in detail for load bearing structures. This paper presents the contribution of plant fibers (i.e. wheat straw) in improving the behavior and capacity of reinforced concrete for structural applications. Reinforced concrete beam-lets with varying flexure and shear rebars, without and with inclusion of wheat straw, are experimentally investigated for studying the altered behavior due to fibers. In addition, to start with the practical implications, concrete pavements are considered. The study is concluded with an increase in flexural strength (up to 7.5%), energy absorption (up to 30.4%), and toughness indices (up to 11.1%) along with better crack arresting mechanism by incorporation of wheat straw in reinforced concrete. Also, concrete pavement containing wheat straw has comparable design with likely more durable and sustainable structure.

1. Introduction

Concrete is a most widely used construction material all over the world. It is basically very strong in compression however it is brittle in nature. Brittleness of concrete results in low strain capacity in tension and thus ultimately have low toughness. Many researchers have been working on increasing the toughness of concrete with the addition of dispersed fibres. So, it has been long recognized as a solution for enhancing the energy absorption capacity, toughness and crack resistance or crack arresting [1–5]. This technique had been used since biblical times for strengthening the brittle matrices. The development of cracks and increase in width of

Abbreviations: A_s, Area of steel (in^2); f_y, Tensile strength of steel (MPa); f_s, Compressive strength of concrete (MPa); FE1, Flexural Energy absorbed up to the First Crack (kN.mm); FE, Total Flexural Energy absorbed (kN.mm); FEM, Flexural Energy absorbed from first crack to the Maximum load (kN.mm); FEP, Flexural Energy absorbed Post the maximum load (kN.mm); FRC, Fibre Reinforced Concrete; FS, Flexural Strength (MPa); FTI, Flexural Toughness Index (i.e. FE/FE1); l_f, Length of fibres; L_1, Load at the First crack (kN); L_m, Maximum Load (kN); L_u, Ultimate Load (kN); MoR,, Modulus of Rupture; M_r, Theoretical Moment Capacity of PC (kN.mm); $M_{PC_{Exp}}$, Experimental Moment Capacity of PC (kN.mm); M_{WSRC}, Theoretical Moment Capacity of WSRC (kN.mm); $M_{WSRC_{Exp}}$, Experimental Moment Capacity of WSRC (kN.mm); NFRC, Natural Fibre Reinforced Concrete; PC, Plain Concrete; T_f, Tensile strength of fibres in tension region (N); T_s, Tensile strength of steel in tension region (N); T_{WSRC}, Tensile strength of straw in tension region (N); V, Shear Capacity (kN); V_f, Volume of fibres in concrete; $V_{PC_{Exp}}$, Experimental Shear Capacity of PC (kN); $V_{PC_{Theo}}$, Theoretical Shear Capacity of PC (kN); $V_{WSRC_{Exp}}$, Experimental Shear Capacity of WSRC (kN); $V_{WSRC_{Theo}}$, Theoretical Shear Capacity of WSRC (kN); WSRC, Wheat Straw Reinforced Concrete; Δ, Deflection; $\varnothing$, Diameter; $\varnothing_f$, Diameter of fibres.

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https://doi.org/10.1016/j.conbuildmat.2018.06.041
0950-0618/

already developed cracks can be prevented using dispersed fibres as crack arresters [6,7]. Biryukovichs used glass as dispersed fibre for the reinforcement of cement paste and mortar in early 1900 [8]. The application of dispersed fibres in the concrete as a building material for different purposes resulted in improved properties [9]. However, the incorporation of fibres in steel reinforced concrete has also been studied by various researchers [7,10–14]. Shear behavior of fibre reinforced concrete (FRC) beams was studied by [11]. Polypropylene fibres with 0.5% and steel fibres with 0.5%, 1%, and 2% content, by volume of wet concrete, were used. The compressive strength and tensile strength were increased up to 54.8 MPa and 4.3 MPa, respectively. High strength fibre reinforced concrete beams with steel rebars were also studied by [13]. The steel ratio used were 0.0017, 0.0064, 0.0075, 0.012, 0.015, and 0.022 for tensile reinforcement. And for compression reinforcement, 0.0045 and 0.0047 steel ratios were used. The percentages content for the steel fibres used were 0.5%, 1%, and 2%, by volume of wet concrete. The study resulted in significant increase of flexural strength. The above-mentioned studies concluded that the fibre reinforced concrete with steel bars showed improved results in crack and deflection resistivity, toughness, and energy absorption.

Natural fibres, due to their abundant production, easy handling, flexibility, and cheap availability are under consideration from past few decades. The use of natural fibres in concrete composites can result in the alternative eco-friendly, sustainable, and economical civil engineering construction materials. Natural fibres are comparable with artificial/steel fibres to be used as dispersed reinforcement in cement composites for having the improved toughness [15–19]. Coir, malva, sugarcane, kenaf bast, bamboo, banana, pineapple leaf, date, sisal, vakka, palm, jute, hemp, elephant grass, Hibiscus cannabinus, abbaca leaf, ramie bast, flax, sansevieria leaf, and wheat straw are the natural fibres which have been studied by different researchers for concrete composites in different aspects [20–27]. The overall cost of natural fibres is very less when compared to the whole cost of cement composites. So, along with the improvement in properties, natural fibres can also add up in reducing the cost [28–31]. The natural fibre reinforced concrete (i.e. concrete reinforced with bamboo bars and reinforced concrete beams along with sisal fabric composites) has been studied by various researchers [32–35]. Flexural and shear cracking strength of Bamboo fibre reinforced concrete members were examined by [32]. The improved properties for bamboo fibre reinforced concrete were reported when compared to that of reinforced concrete. Similar type of results were observed in case of chemically treated bamboo fibre reinforced concrete [35]. However, in addition to enhance the capacity of energy absorption and toughness of cement concrete composites by the incorporation of natural fibres, the durability of natural fibres must also be taken in account properly [15].

Among all natural fibres; various researchers have been considering the different types of straw (i.e. wheat, rape, barely, and rice) now a day, due to their production in abundance in sub-tropical regions. These straw are studied to be used in mud mortar composites, brick earth, cement-sand mortar, straw boards, bales, and soil etc. as a civil engineering construction material for various applications [20,36–47]. Wheat straw is the end product of wheat crop and usually available in surplus to requirements in many countries. Therefore, due to its cheap availability and easy access, the use of wheat straw in civil engineering applications will be effective [47]. As a dispersed reinforcement and straw bales, wheat straw have already been used for concrete composites, and structural members, respectively by various researchers. Enhancement in the compressive strength of straw bales was reported by Ashour et al. [38]. Straw bales were examined as structural member in that study. Merta et al. investigated the fracture energy of hemp, wheat straw, and elephant grass reinforced concrete [20]. An increase of 70%, 2%, and 5% in the fracture energy of optimized hemp, wheat straw, and elephant grass reinforced concrete, respectively, was observed when compared to that of plain concrete. The optimized length and content of natural fibres used were 40 mm and 0.19%, by mass of wet concrete, respectively. Wheat straw reinforced cement mortar was also investigated by Albahttiti et al. [46]. The percentage contents of short and long wheat straw used were ranged from 0.5% to 5%, by volume. Flexural and compressive behaviors of wheat straw reinforced cement mortar were explored. The stiffness of the considered matrix with the straw content of 0.75%, by volume, was increased by 23% as compared to that of plain cement mortar. Hence, based on the studies conducted on wheat straw reinforced composites, wheat straw can be used as dispersed reinforcement in cement concrete composites for different civil engineering structural and non-structural applications.

To the best of author's knowledge, in spite of the fact that, many studies on plant fibres (especially wheat straw) reinforced composites have already been made by a number of researchers for the civil engineering non-structural applications [38,39,41,42]. But, the plant fibres, as dispersed reinforcement, in cement concrete composites are slightly explored yet. Although, wheat straw reinforced cement composites, with enhanced properties, were reported by Albahttiti et al. and Merta et al. [20,46]. The study on wheat straw reinforced concrete for building material applications [20] concluded in an increase of 2% in its fracture energy. And, an increase of 23% in stiffness of wheat straw reinforced cementitious composites was observed [46]. This is perceived that this enhancement in properties of wheat straw reinforced cement composites in comparison with controlled composites might be due to the rough surface of straw after simple pre-treatment, which forms relatively better bonding between straw and cement matrix as in interlocking phenomenon. This better bonding between straw and matrix provides the sewing effect which enhances the energy absorption of composite by resisting the crack formation and propagation. Therefore, on the basis of indication of improved properties by these studies [20,46], there is a need to study plant fibre (i.e. wheat straw) reinforced concrete in detail for its various properties along with its behavior especially for civil engineering structural applications. However, to the best of author's knowledge, no study has been made on in-depth behavior and capacities of wheat straw reinforced concrete with steel rebars. Hence, in the current study, the contribution of plant fibre (i.e. wheat straw) is studied for enhancing the capacities and improving the behavior of concrete reinforced with flexural and shear steel rebars for its use in civil engineering structural applications especially in concrete pavements. Beam-lets of Plain Concrete (PC), and Wheat Straw Reinforced Concrete (WSRC) with the flexural and shear reinforcement are studied under flexural loading. The flexural strength and behavior (i.e. primary parameter for design of concrete pavements) are investigated for the possible application of WSRC in rigid pavements. In addition to this, the moment capacity design equation and concrete pavement thickness design equation are proposed and theoretical and experimental results are discussed. Wheat straw reinforced concrete with steel rebars can be used in pavements for increasing its load bearing capacities, crack resistance, and to avoid the crack propagation under traffic loading.

2. Experimental investigation

2.1. Raw materials

The ingredients that are used for preparing PC, and WSRC are the Ordinary Portland Cement from the brand which is available locally, lawrence-pur sand, Margallah crush/aggregates, tap/potable water and the wheat straw that are available commercially. The size of aggregates used is restricted up to 20 mm. Wheat straw,