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.

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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
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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, extracted from agricultural residues, are obtained from a near-by source. A random selection is made to get the commercially available wheat straw. The average dimensions of wheat straw are approximately 25 mm × 5 mm × 1.2 mm. The average is being obtained from randomly selected wheat straw. The physical properties of wheat straw were determined experimentally by [48,49]. The density of straw ranged from 865 to 871 kg/m^3. Whereas, the water absorption capacity of wheat straw was up to three times of it's own weight at 20 °C. The tensile and shear strength of wheat straw ranged from 21.2 to 31.2 MPa and 4.91 to 7.26 MPa, respectively. The chemical analysis of wheat straw was done by [50] as reported by [51]. The primary chemical composition of wheat straw after chemical analysis showed that it was rich in carbohydrates (i.e. hemicellulose, cellulose, and lignin). Minerals (i.e. calcium and phosphorus), proteins, silica, acid detergent fibres and ash were also present in straw along with 84–91% dry matter. The presence of wax, dry, and dust particles on the surface of straw can result in poor bond between straw and concrete matrix. Hence, for removal of wax, dry, and dust particles from the surface of straw, some preparation/treatment is required. Therefore, for this purpose, a simple pre-treatment technique is adopted in order to ensure the straw as a low-cost construction material. In this pre-treatment technique, the wheat straw are remained soaked in water for a quarter hour. After that, straw are air surface dried. This process is adopted for having a better bond between straw and cement concrete composite. These prepared straw are used as dispersed reinforcement for making WSRC and are shown in Fig. 1. The longitudinal and transverse reinforcement in PC and WSRC beam-lets are the ∅6 steel rebars of Grade – 280 (i.e. f_y = 280 MPa). The diameter of steel rebars is same (i.e. ∅6) for both longitudinal and transverse reinforcement.

2.2. Mix design and procedure for casting

The cement, sand, and aggregate proportions for preparing the plain concrete are 1, 2, and 4, respectively. The water-cement ratio used in preparation of PC is 0.55. All the materials (i.e. cement, sand and aggregates) are put simultaneously in the drum mixer for preparing the PC mix. Water is added at the end. The mixer is rotated for five minutes to have a homogenous PC mix. However, for the preparation of wheat straw reinforced concrete, straw are put in the mixer having fresh plain concrete. The percentage content and approximate length of straw are 1%, by mass of plain concrete, and 25 mm, respectively. The water-cement ratio for WSRC is 0.60. The mixer is then rotated for two minutes to get WSRC mix. The WSRC mix is not seemed to be workable and homogenous at that stage. The mixer is again rotated for two minutes for having the homogenous and better WSRC mix. Because at this stage, bleeding from WSRC mix can be occurred in result of adding more water. Therefore, the mixing time is increased which resulted in a successful approach for having a homogenous and workable WSRC mix. The slump test for PC, and WSRC is performed. The value of slump for PC and WSRC is 40 mm and 20 mm, respectively. It may be noted that a decrease in slump of WSRC as compared to that of PC is observed in spite of the fact that that the water – cement ratio in case of WSRC is more than that for PC. This might be due to the fact that a considerable amount of water is absorbed by the air-surface dried straw in WSRC mix.

Fig. 1. Prepared wheat straw.

The prepared PC and WSRC is then poured in the beam-let moulds having steel bars tied with stirrups in three successive layers for the preparation of PC and WSRC specimens followed by 25 blows of tamping rod after each layer. Whereas, in case of WSRC, the lifting (i.e. 100–150 mm) and free falling of the beam-let moulds after each layer is done for self-compaction by removing air voids. The de-moulding of specimens is done after 24 h and are kept in water tank for the curing of 28 days before testing. The designated 28 days compressive strength of 1:2:4 PC mix is 20 MPa. However, for this scenario, 100 mm diameter and 200 mm high cylinder specimens of PC and WSRC are cast and tested under compressive loading. The calculated compressive strengths of PC and WSRC range from 22.3 to 22.8 MPa and 21.5 to 22.0 MPa, respectively. And, for calculating Modulus of Rupture (MoR), 102 × 102 × 457 mm beam-let specimens are cast and tested under flexural loading. The calculated MoR of PC and WSRC range from 3.02 to 3.58 MPa, and 3.24 to 3.61 MPa, respectively.

2.3. Specimens

Beam-lets of 102 mm width, 102 mm depth and 457 mm length are cast for PC and WSRC with flexural and shear steel rebars to perform the flexural strength test. A total of ten beam-lets (i.e. five for PC and five for WSRC) are cast. The reason for casting beam-lets is to get an indication of flexural strength of WSRC with steel rebars keeping in mind the primary parameter (i.e. flexural strength) in design of rigid pavements for resisting vehicular loading. These beam-lets are considered as prototypes. One specimen for each combination of PC and WSRC is cast. Other researchers also considered one prototype for one combination [52–54]. It may also be noted that averaged material properties are being taken. For flexural reinforcement, the number of ∅6 bars are varied by 2, 3, and 4 bottom bars by having steel ratios of 0.016, 0.020, and 0.025, respectively. Keeping in mind the placement of rebars in the beam-let moulds having width of 102 mm only, the smaller diameter rebars (i.e. ∅6 steel rebars) are used in all the specimens. However, the stirrups spacing is kept constant i.e. 76 mm. Whereas, in case of varied shear reinforcement, the stirrups spacings are varied by 64, 76, and 89 mm but the number of longitudinal bars is kept constant i.e. 3 bottom bars. It may be noted that the relative comparison between reinforced concrete (RC) and WSRC with steel rebars is made. So, longitudinal and transverse rebars diameter in a particular combination of RC and WSRC with steel rebars is kept same. Labelling scheme for PC and WSRC specimens with flexural and shear steel rebars is given in Table 1. However, the flexural and shear reinforcement detailing for PC and WSRC is shown in Fig. 2.

2.4. Testing methodology

2.4.1. Flexural test

For studying the flexural behavior of PC and WSRC with flexural and shear reinforcement and for the determination of flexural strength (FS), flexural energies absorbed (i.e. FE1, FEM, FEP, and FE), and flexural toughness index (FTI), beam-lets are tested in the flexural testing machine as per ASTM C78–02. The servo-hydraulic machine is used to apply the flexural load. A dial gauge is attached at the mid of beam-lets to record the mid-span deflection. The testing setup i.e. schematic diagram and experimental

Table 1
Labelling scheme of PC and WSRC beam-lets with steel rebars.

Sr. No.	Flexural	Shear	Steel ratio (ρ)	Labels	
				PC	WSRC
(1)	(2)	(3)	(4)	(5)	(6)
1.	2-∅6	∅6–76 mm	0.016	PCF1	WSF1
2.	3-∅6	∅6–76 mm	0.020	PCF2/PCS2	WSF2/WSS2
3.	2 + 2-∅6	∅6–76 mm	0.025	PCF3	WSF3
4.	3-∅6	∅6–64 mm	0.020	PCS1	WSS1
5.	3-∅6	∅6–89 mm	0.020	PCS3	WSS3

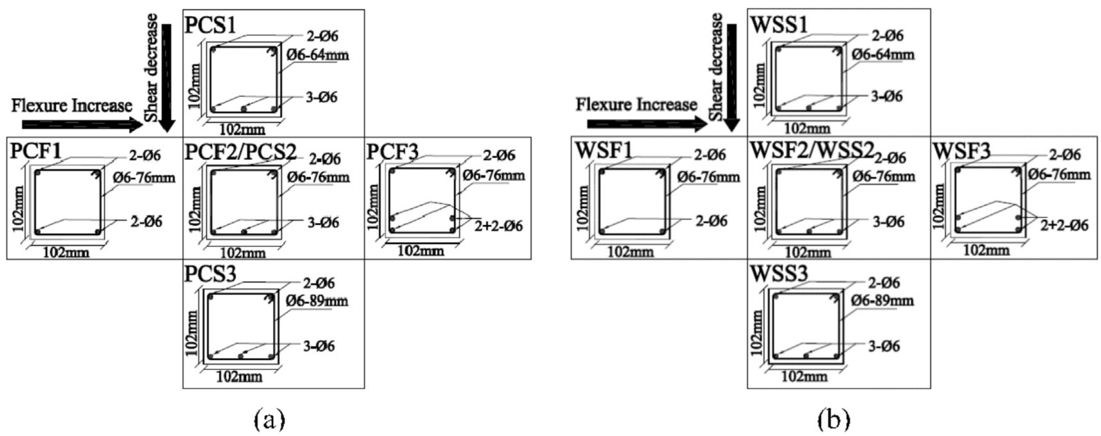

Fig. 2. Beam-lets cross-sections of PC and WSRC with flexural and shear reinforcement detailing (a) PC, and (b) WSRC.

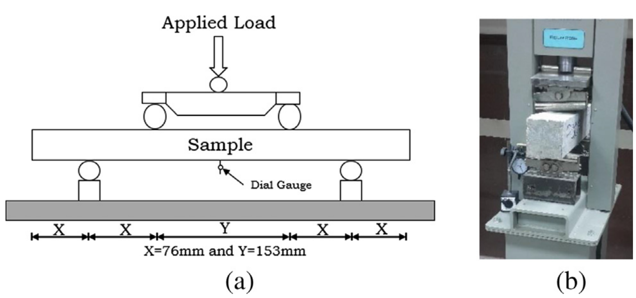

Fig. 3. Testing setup (a) Schematic diagram, and (b) Experimental setup.

setup is shown in Fig. 3. The crack propagation in the beam-lets under the flexural loading and the load – deflection curves are recorded. Crack propagation is observed with visual inspection. And, the first crack is noted/observed with the naked eye and the corresponding load is recorded. The load at which first crack is occurred (L_1), the maximum load (L_m), the ultimate load (L_u), the maximum deflection (Δ), the number of cracks at ultimate load, and failure mode are extracted from this information.

3. Test results and analysis

3.1. Properties under flexural loading

3.1.1. Specimens with varying flexural and constant shear reinforcement (i.e. ∅6–76 mm)

3.1.1.1. Flexural behavior of specimens with varying flexural steel rebars. The load-deflection curves of PC and WSRC beam-lets with varying flexural reinforcement and constant shear reinforcement (i.e. ∅6–76 mm) are shown in Fig. 4. For PC and WSRC with varying flexural reinforcement and constant shear reinforcement (i.e. Ø6–76 mm), the first crack, cracks at the maximum loading, cracks at the ultimate loading, and the tested beam-let specimens are shown in Fig. 5. In case of both PC and WSRC, the flexural reinforcement is increased by 2-Ø6, 3-Ø6, and 2 + 2 – Ø6. The linear behavior is observed in all the load-deflection curves until the appearance of first crack. However, post the first crack, an improved behavior of WSRC specimens can be observed as less steepness in the curve and more deflection before the ultimate load can be noted compared to that of PC, indicating towards the tough behavior of WSRC. As far as WSRC with flexural reinforcement is observed, the specimen with the steel rebars of 3-∅6 shows the more tough behavior compared to the other WSRC specimens. The behaviors of PC and WSRC specimens, with flexural steel reinforcement, under the flexural loading are also observed. Certain information i.e. first crack length and number of cracks at the maximum load and at the ultimate load are revealed. The first cracks in case of PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are appeared at 84.1%, 83.7%, 91.2%, 89.2%, 92.9%, and 90.5%, respectively, of their respective peak loads. However, the severity of cracks, that is observed with naked eye, in case of WSRC specimens is less than in case of PC specimens. The observed length of the first crack in WSRC beam-lets is also less than that of the respective PC beam-lets. It is also noted that the first crack length is decreased with increase in flexural reinforcement. The length of the first crack in PCF1, PCF2, and PCF3 beam-lets is approximately 89 mm, 70 mm, and 63 mm, respectively, and it is approximately 63 mm, 54 mm, and 51 mm in WSF1, WSF2, and WSF3 beam-lets, respectively. At the maximum loading, the cracks width and length, and the number of cracks, are more in PC specimens when compared to that in respective WSRC specimens. Again, at the ultimate load, the number of cracks, cracks width and length are slightly more than that observed at the maximum load. It is observed that although the number of cracks in WSRC specimens are slightly more or equal in some cases in comparison with PC. But the crack width or severity in PC specimens is much more as compared to WSRC specimens, when noted with the naked eye.

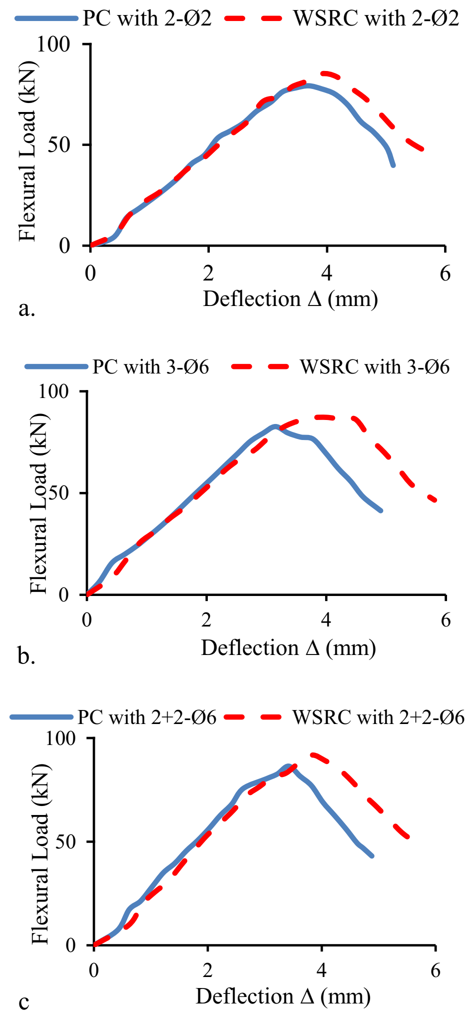

Fig. 4. Load – deflection curves of PC and WSRC with flexural reinforcement (a) 2-∅6, (b) 3-∅6, and (c) 2 + 2-∅6 and constant shear reinforcement (i.e. ∅6–76 mm).

It is found that WSRC beam-lets perform better than that of PC beam-lets. The utilization of wheat straw in concrete enhanced the post cracking performance of tested beams-lets.

3.1.1.2. Effect of flexural steel rebars on load, deflection and cracks. The load details, maximum deflections, number of cracks occurred at ultimate failure, and failure modes for PC and WSRC with varying flexural reinforcement and constant shear reinforcement (i.e. ∅6–76 mm) are given in Table 2. The load at which the first crack occurred is taken from the load–deflection curves of respective tested beam-lets. The load at which first crack occurs for PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are 66.7 kN, 71.4 kN, 75.4 kN, 77.6 kN, 80.3 kN, and 83.0 kN, respectively. The load at which first crack occurs of WSF1, WSF2, and WSF3 are increased by 4.7 kN, 2.2 kN, and 2.7 kN, respectively, when compared with that of PCF1, PCF2, and PCF3, respectively. Here, it can be noted that the crack resistance of WSRC is more than that of PC as the first cracks are occurred at comparatively high loads in case of WSRC beam-lets in comparison with PC beam-lets. This crack resistance is due to the incorporation of straw in the concrete composite. A linear increase is observed in load at which first crack occurs for both PC and WSRC beam-lets with increasing flexural rebars and constant shear rebars. Similarly, the maximum load is also taken from the load-deflection curve of the tested specimens. The maximum load for PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are 79.3 kN, 85.3 kN, 82.7 kN, 87.0 kN, 86.4 kN, and 91.8 kN, respectively. The maximum load of WSF1, WSF2, and WSF3 are increased by 7.5%, 5%, and 6%, respectively, when compared with that of PCF1, PCF2, and PCF3, respectively. The observed trend in case of maximum load is similar to that as observed in case of load at first crack. Similarly, the ultimate load of WSF1, WSF2, and WSF3 are increased by 13.8%, 12.6%, and 10%, respectively, when compared to the ultimate load of PCF1, PCF2, and PCF3, respectively. Overall, the addition of wheat straw in concrete increases the load carrying capacities of the WSRC beam-lets. The maximum deflection (Δ) of PC and WSRC beam-lets is recorded with the help of dial gauge. The values of maximum deflection are also given in Table 2. The maximum deflections which are occurred in case of WSRC specimens are more than that in case PC specimens. The Δ for PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are 5.12 mm, 5.76 mm, 4.91 mm, 5.81 mm, 4.88 mm, and 5.76 mm. however, the decrement in the mid-span deflection is observed in the specimens with increased flexural reinforcement. This decrease in deflections at mid-spans is might be due to the increase in stiffness of the respective beam-lets with increased flexural reinforcement. The stiffness of the beam-lets is proportional with the steel ratio [7]. The number of cracks at the ultimate failure in tested beam-lets is also noted and is also given in Table 2. The number of cracks in PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 beam-lets are 4, 3, 4, 3, 3, and 2, respectively. The crack lengths and crack widths in PC beam-lets are more than that in WSRC beam-lets. The reason behind the relatively less crack width and smaller crack length in WSRC beam-lets than that in PC beam-lets is the presence of wheat straw. Due to the presence of wheat straw, the bridging phenomenon and crack arresting is observed in WSRC specimens. The straw resists the development of first cracks firstly, then the crack propagation is also resisted due to the arresting of cracks with straw. The failure mode of the tested beam-lets, which is observed on the basis of cracks formation, are given Table 2. The observed failure mode for PCF1 and WSF1 is flexural, for PCF2 and WSF2 is balanced, and that for PCF3 and WSF3 is shear. Flexural failure mode indicates that the failure is caused by flexural cracks, shear failure mode indicates that the failure is caused by shear cracks (i.e. propagated at 45°), and balanced failure mode indicates that the number of flexural and shear cracks are almost the same at the time of ultimate failure.

A close-up view of fibre/straw and concrete interaction in the composite at the broken surface of WSRC beam-let with steel rebars is shown in Fig. 6. The broken surface of the specimen is examined with the naked eye for observing the straw failure mechanism in the concrete composite. It is noted that, as an approximation, there is a ratio of 70:30 in the straw failure between fracture and pulling-out of straw. The fracture mechanism of straw is observed in the case where there is an almost equal development length of straw at both sides of fracture surfaces. It shows that the bond strength between straw and matrix is more than tensile strength of straw. However, the straw pull-out phenomenon is occurred in case of less embedded length of straw at any one side of fractured surfaces. It shows that the bond strength at one side between straw and matrix is less than the tensile strength of wheat straw.

3.1.1.3. Effect of flexural rebars on flexural strength, flexural energies absorbed, and flexural toughness index. The flexural strength (FS), flexural energies absorption, and flexural toughness index (FTI) of beam-lets with varying flexural reinforcement and constant shear reinforcement (i.e. ∅6–76 mm) are given in Table 3. The flexural strength of PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are calculated by using the maximum load from the load–deflection curves of the respective specimens. The flexural strengths of PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are 34.6 MPa, 37.2 MPa, 36.0 MPa,

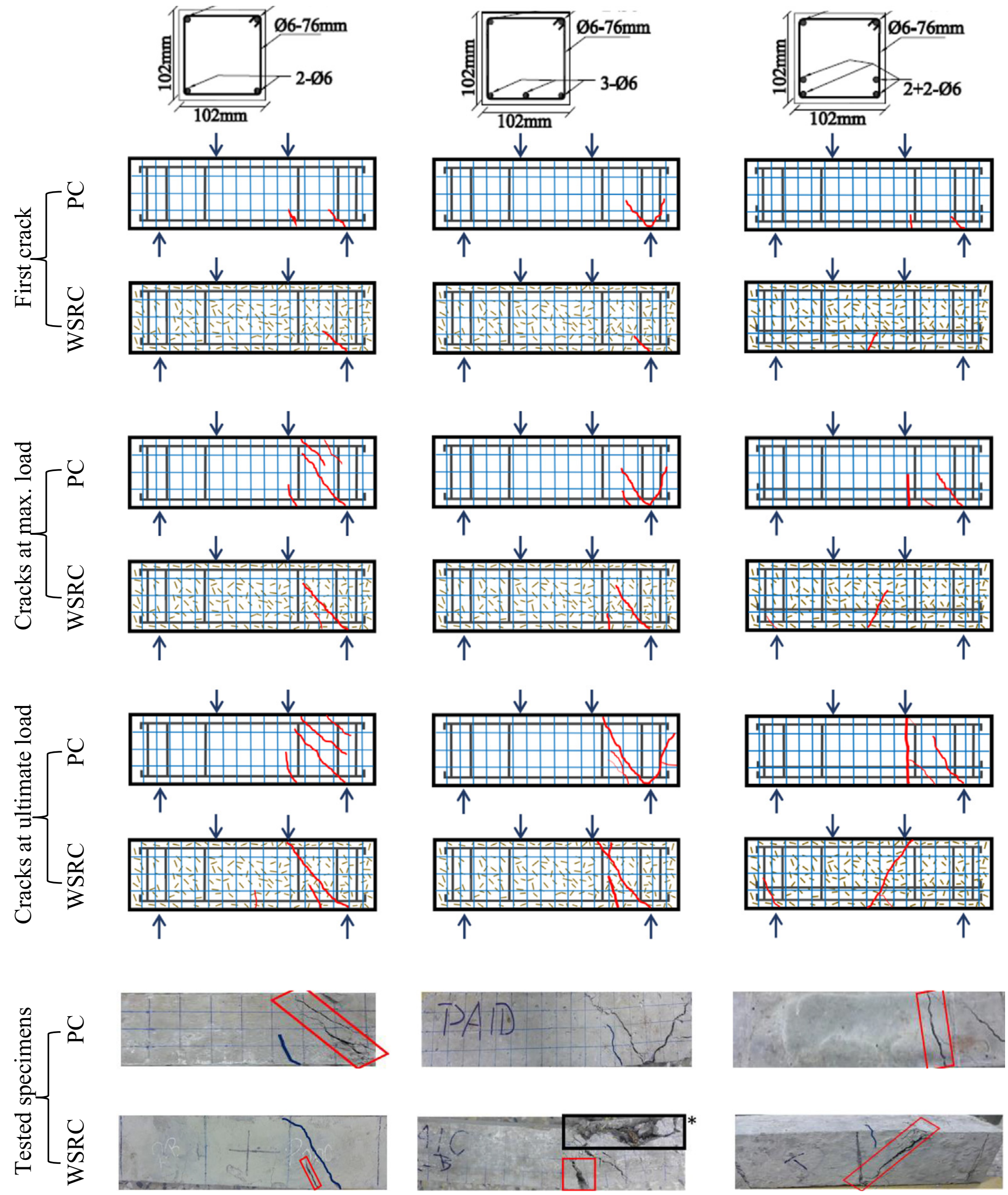

Fig. 5. Crack behavior of PC and WSRC specimens during flexural loading with varying flexural reinforcement and constant shear reinforcement (i.e. $\varnothing$6–76 mm).

Table 2
Loads and Deflections for tested PC and WSRC beam-lets with varying flexural reinforcement and constant shear reinforcement (i.e. $\varnothing$6–76 mm).

Loads and Deflections	Specimens					
	PC			WSRC		
(1)	2-$\varnothing$6 (2)	3-$\varnothing$6 (3)	2 + 2-$\varnothing$6 (4)	2-$\varnothing$6 (5)	3-$\varnothing$6 (6)	2 + 2-$\varnothing$6 (7)
Load at First Crack (kN)	66.7	75.4	80.3	71.4	77.6	83.0
Maximum Load (kN)	79.3	82.7	86.4	85.3	87.0	91.8
Ultimate Load (kN)	39.8	41.3	43.1	45.3	46.5	47.4
Maximum Deflection (mm)	5.12	4.91	4.88	5.76	5.81	5.76
Cracks at Ultimate Load (–)	4	4	3	3	3	2
Failure Mode (–)	Flexure	Balanced	Shear	Flexure	Balanced	Shear

38.2 MPa, 37.7 MPa, and 40.1 MPa, respectively. An increase of 7.5%, 5.8%, and 6.2% in flexural strengths of WSF1, WSF2, and WSF3, respectively, is observed when compared to that of PCF1, PCF2, and PCF3, respectively. The area under the load-deflection curve up to load, at which first crack occurred, is taken as energy absorption up to first crack (FE1). The FE1 of WSF1, WSF2, and WSF3 are increased by 5.9 kN.mm, 17.7 kN.mm, and 18.4 kN.mm, respectively, when compared with that of PCF1, PCF2, and PCF3,

Fig. 6. Straw – concrete interaction with naked eye.

respectively. The increase in FE1 for PC and WSRC specimens is observed with an increase in flexural reinforcement. The area under load-deflection curve from first crack load to maximum load is taken as energy absorbed from first crack to maximum load (FEM). The FEM of WSF1, WSF2, and WSF3 are increased by 19%, 82%, and 34%, respectively, as compared to that of PCF1, PCF2, and PCF3, respectively. The convex decrease is observed here in FEM for both PC and WSRC beam-lets with increase in flexural reinforcement. Flexural energy absorbed from maximum load to ultimate load (FEP) is taken as the area under load-deflection curve from maximum load to ultimate load. The FEP of PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are 93.9 kN.mm, 118.4 kN.mm, 115.1 kN.mm, 147.4 kN.mm, 95.0 kN.mm, and 137.5 kN.mm, respectively. Again, the FEP of WSRC specimens are more than that of PC specimens. The total area under load – deflection curve or the summation of FE1, FEM, and FEP is taken as total flexural energy absorbed (FE). The similar increasing trend in energies absorbed by WSRC specimens as compared to energies absorbed by PC specimens is observed here. An overall increase of 17%, 30%, and 27% in the FE of WSF1, WSF2, and WSF3, respectively, is observed when compared to that of PCF1, PCF2, and PCF3, respectively. The ratio of total flexural energy absorbed to the flexural energy absorbed up to load at which occurrence of first crack takes place (i.e. FE/FE1) is taken as flexural toughness index. The flexural toughness index of PCF1, WSF1, PCF2, WSF2, PCF3, and WSF3 are 2.75, 3.02, 2.43, 2.70, 2.02, and 2.32, respectively. The flexural toughness index of WSF1, WSF2, and WSF3, are increased by 10%, 11%, and 10%, respectively, when compared with that of respective PC specimens. A slight increase in toughness index of the specimens with flexural reinforcement of 3-∅6 is observed, when compared to other WSRC matrix. It may be noted that over all the FS, FE1, and FE are increased with an increase in flexural reinforcement, but a decrement is observed in FEM, FEP and FTI. The reason for the decrease in FEM is might be the reduction of gap between first crack load and maximum load due to which area under the curve from first crack load to maximum load reduces.

A comprehensive comparison of FS, FEP, FE, FTI, and deflection (Δ) of PC and WSRC with varying flexural reinforcement (i.e. 2-∅6, 3-∅6, and 2 + 2-∅6) and with constant shear reinforcement (i.e. ∅6–76 mm) is shown in Fig. 7. Overall, all the WSRC specimens with flexural steel rebars are performed better than respective PC specimens. The improved properties of WSRC in terms of flexural strength, the post cracking behavior, and toughness are observed in comparison to PC. In result of which more displacement is also noted for WSRC specimens with flexural steel rebars. As far as WSRC specimens are concerned, only the FEP in case of specimen with 3-∅6 flexural reinforcement and ∅6–76 mm shear reinforcement is significantly higher than other considered WSRC specimens. Otherwise all the other properties are more or less same with slight variation i.e. increase in properties with an increase in flexural reinforcement.

3.1.2. Specimens with varying shear and constant flexural reinforcement (i.e. 3-∅6)

3.1.2.1. Flexural behavior of specimens with varying shear steel rebars. The load – deflection curves of PC and WSRC with shear reinforcement (i.e. ∅6–64 mm, ∅6–76 mm, and ∅6–89 mm) and with constant flexural reinforcement (i.e. 3-∅6) are shown in Fig. 8. For PC and WSRC with constant flexural reinforcement (i.e. 3-∅6) and varying shear reinforcement, the first crack, cracks at the maximum loading, cracks at the ultimate loading, and the tested beam-let specimens are shown in Fig. 9. In case of both PC and WSRC, the shear reinforcement is decreased by ∅6–64 mm, ∅6–76 mm, and ∅6–89 mm. Here again, the flexible behavior and toughness of WSRC specimens with shear steel rebars can be observed from load-deflection curves in comparison to respective PC specimens. The more displacement in case of WSRC specimens

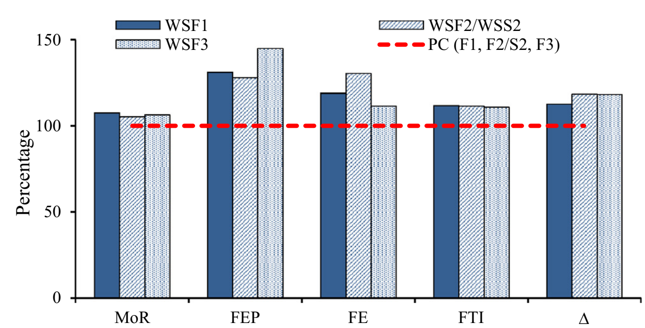

Fig. 7. Comparison of FS, FEP, FE, FTI, and Δ of PC and WSRC with varying flexural reinforcement (i.e. 2-∅6, 3-∅6, and 2 + 2-∅6) and with constant shear reinforcement (i.e. ∅6–76 mm).

Table 3
Flexural strengths, Flexural energies absorbed (FE1, FEM, FEP, FE), and Flexural Toughness Index (FTI) for PC and WSRC beam-lets with varying flexural reinforcement and constant shear reinforcement (i.e. ∅6–76 mm).

Properties	Specimens					
	PC			WSRC		
(1)	2-∅6 (2)	3-∅6 (3)	2 + 2-∅6 (4)	2-∅6 (5)	3-∅6 (6)	2 + 2-∅6 (7)
FS (MPa)	34.6	36.0	37.7	37.2	38.2	40.1
FE1 (kN.mm)	91.0	104.1	125.9	96.9	121.8	144.3
FEM (kN.mm)	65.6	33.3	33.2	77.9	60.0	40.4
FEP (kN.mm)	93.9	115.1	95.0	118.4	147.4	137.5
FE (kN.mm)	250.5	252.5	254.1	293.3	329.2	322.1
FTI (–)	2.75	2.43	2.02	3.02	2.70	2.23

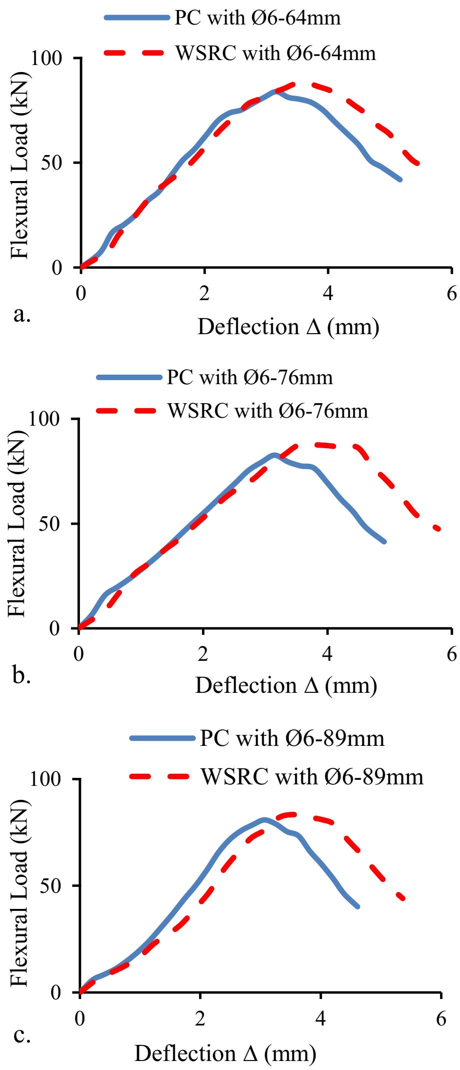

Fig. 8. Load – deflection curves of PC and WSRC with shear reinforcement (a) ∅6–64 mm, (b) ∅6–76 mm, and (c) ∅6–89 mm and constant flexural reinforcement (i.e. 3-∅6).

with shear reinforcement is observed. This is due to the presence of wheat straw. The resistance to cracking and the crack arresting behavior is occurred due to which the WSRC specimens show more displacement and bear load for more time as compared to that in case of respective PC specimens. In case of WSRC specimens, the beam-let with shear reinforcement of ∅6–76 mm shows the relatively better behavior in comparison to other considered WSRC specimens. As in that case, an improved behavior after the maximum load is noted. The cracking mechanism in the PC and WSRC specimens with shear reinforcement (i.e. shear steel rebars) is also observed while testing. The formation of cracks at the different levels (i.e. first crack, at maximum loading, and at the ultimate loading) is revealed. The first cracks in case of PCS1, WSS1, PCS2, WSS2, PCS3, and WSS3 are appeared at 89.5%, 91.3%, 91.2%, 88.6%, 93.8%, and 91.3%, respectively, of their respective maximum loads. The width and severity of first cracks is relatively much lesser than that cracks which are occurred at maximum and ultimate loading in case of PC. The crack resistance in WSRC specimens with more shear reinforcement (i.e. ∅6–64 mm) is more than that of all other considered specimens. The lengths of the first crack in WSRC beam-lets, that are observed with naked eye, are also less than that of the respective PC beam-lets. It can be noted with the naked eye that the cracks length and width, and the number of cracks, are more in PC beam-lets when compared to that in respective WSRC specimens. It is found that the crack resistance in WSRC beam-lets with shear reinforcement is much better than that in PC beam-lets. However, among all WSRC specimens with shear reinforcement, the one with the minimum shear reinforcement of ∅6–64 mm and flexural reinforcement of 3-∅6 shows better crack arresting as compared to other considered WSRC specimens. An enhancement in the post-cracking behavior, due to the incorporation of wheat straw, is observed.

3.1.2.2. Effect of shear steel rebars on load, deflection and cracks. Loads, deflections, number of cracks occurred at ultimate failure, and failure modes for tested PC and WSRC beam-lets with varying shear reinforcement (i.e. ∅6–64 mm, ∅6–76 mm, and∅6–89 mm) and with constant flexural reinforcement (i.e. 3-∅6) are given in Table 4. The first crack load for PCS1, WSS1, PCS2, WSS2, PCS3, and WSS3 are 75.2 kN, 80.4 kN, 75.4 kN, 77.6 kN, 75.9 kN, and 76.1 kN, respectively. The load at first crack of WSS1, WSS2, and WSS3 are increased by 6.9%, 2.9%, and 0.3%, respectively, when compared with that of PCS1, PCS2, and PCS3, respectively. It can be found that the improved crack resistance is due to the incorporation of wheat straw in the concrete. The crack resistance is decreased with the decrease in shear reinforcement. The maximum load is also taken from the load-deflection curve of the tested specimens. The maximum load for PCS1, WSS1, PCS2, WSS2, PCS3, and WSS3 are 83.9 kN, 88.1 kN, 82.7 kN, 87.6 kN, 80.9 kN, and 83.4 kN, respectively. The maximum load of WSS1, WSS2, and WSS3 are increased by 4.2 kN, 4.9 kN, and 2.5 kN, respectively, when compared with that of PCS1, PCS2, and PCS3, respectively. Similarly, the ultimate load of WSS1, WSS2, and WSS3 are increased by 7.2%, 14.8%, and 9.7%, respectively, when compared to the ultimate load of PCS1, PCS2, and PCS3, respectively. In general, the load carrying capacities of WSRC specimens with shear reinforcement are enhanced. The values of maximum deflection are also given in Table 4. The maximum deflections which are occurred in case of WSRC specimens are more than that in case PC specimens. An increase of 10.5%, 17.7%, and 16.3% in the deflections of WSS1, WSS2, and WSS3 specimens is observed when compared to that of PCS1, PCS2, and PCS3 specimens. The number of cracks at the ultimate failure in tested beam-lets are also noted by the naked eye and is also given in Table 4. The number of cracks in PCS1, WSS1, PCS2, WSS2, PCS3, and WSS3 beam-lets are 4, 3, 4, 3, 4, and 4, respectively. The crack lengths and crack widths in PC beam-lets are more severe than that in respective WSRC beam-lets. Here again as in case of WSRC with flexural reinforcement, due to the presence of wheat straw, the bridging phenomenon and crack arresting is observed. The straw resists the development of first cracks firstly, then the crack propagation is also resisted due to the arresting of cracks with the help of straw as in case of all WSRC specimens with flexural and shear reinforcement. The failure mode of the tested beam-lets is also observed on the basis of cracks formation and are given in Table 4. The observed failure mode for PCS1 and WSS1 is diagonal tension, for PCS2 and WSS2 is balanced, and that for PCS3 and WSS3 is shear. Here the diagonal tension failure mode indicates the combination of shear and longitudinal stress.

3.1.2.3. Effect of shear rebars on flexural strength, flexural energies absorbed, and flexural toughness index. The flexural strength (FS), flexural energies absorbed, and flexural toughness index (FTI) for PC and WSRC beam-lets with varying shear reinforcement (i.e. ∅6–64 mm, ∅6–76 mm, and ∅6–89 mm) and constant flexural reinforcement (i.e. 3-∅6) are given in Table 5. The flexural strengths of PCS1, WSS1, PCS2, WSS2, PCS3, and WSS3 are calculated by using the maximum load from the load–deflection curves

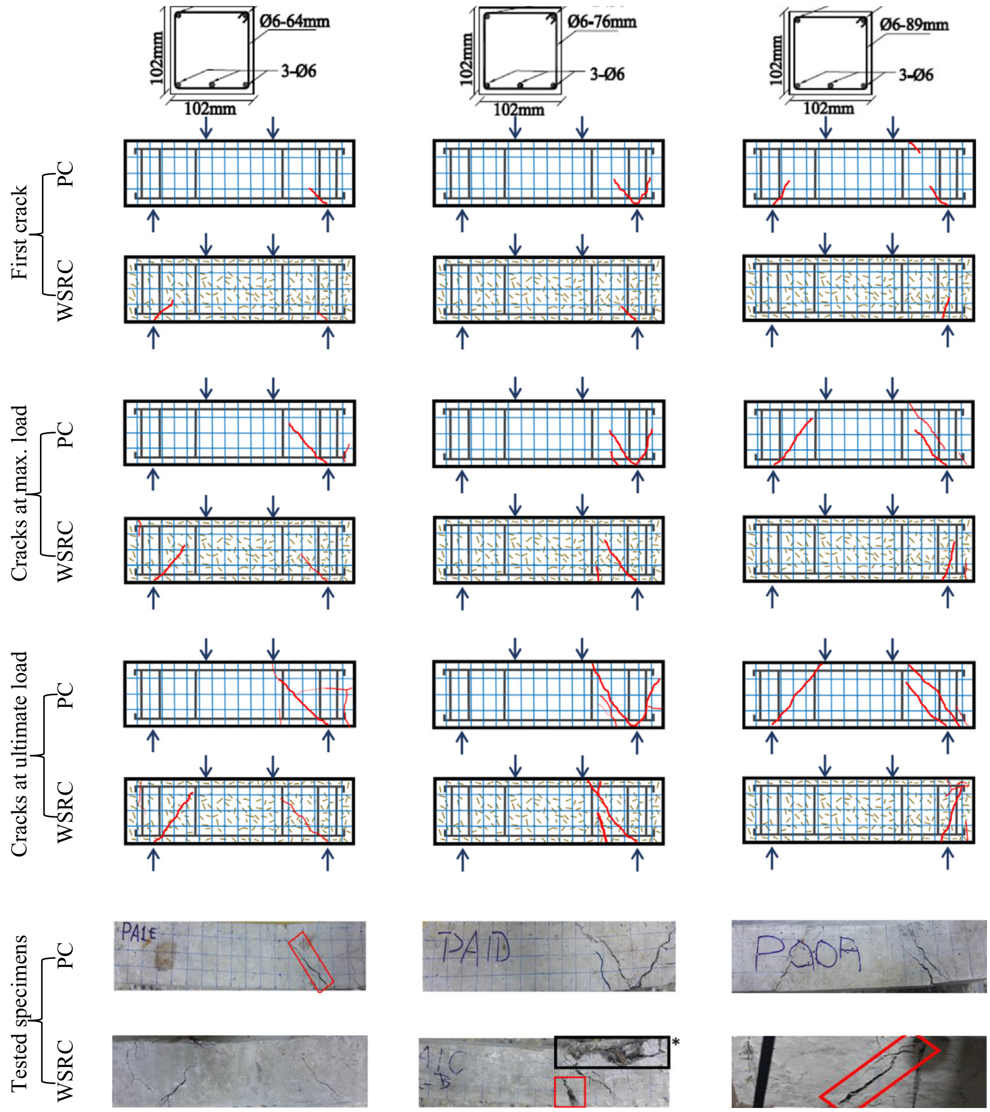

Fig. 9. Crack behavior of PC and WSRC specimens during flexural loading with varying shear reinforcement and constant flexural reinforcement (i.e. 3-∅6).

Table 4
Loads and deflections for tested PC and WSRC beam-lets with varying shear reinforcement and constant flexural reinforcement (i.e. 3-∅6).

Loads and Deflections	Specimens					
	PC			WSRC		
(1)	∅6–64 mm (2)	∅6–76 mm (3)	∅6–89 mm (4)	∅6–64 mm (5)	∅6–76 mm (6)	∅6–89 mm (7)
Load at First Crack (kN)	75.2	75.4	75.9	80.4	77.6	76.1
Maximum Load (kN)	83.9	82.7	80.9	88.1	87.6	83.4
Ultimate Load (kN)	41.9	41.3	40.2	44.9	47.4	44.1
Maximum Deflection (mm)	5.16	4.91	4.61	5.70	5.78	5.36
Cracks at Ultimate Load (–)	4	4	4	3	3	4
Failure Mode (–)	Diagonal tension	Balanced	Shear	Diagonal tension	Balanced	Shear

of the respective specimens. The flexural strengths of PCS1, WSS1, PCS2, WSS2, PCS3, and WSS3 are 36.6 MPa, 38.4 MPa, 36.0 MPa, 38.2 MPa, 35.3 MPa, and 36.4 MPa, respectively. Flexural strengths of WSS1, WSS2, and WSS3 are increased by 4.9%, 5.8%, and 3.1%, respectively, when compared to that of PCS1, PCS2, and PCS3, respectively. Here a decrease in flexural strength of WSRC specimens is observed with the decrease in shear reinforcement. The FEM and FE of WSS1, WSS2, and WSS3 are increased by 42.5%, 81.9%, and 82.2% and 16.8%, 30%, and 21.1%, respectively, as compared to that of PCS1, PCS2, and PCS3, respectively. As for as the FEP of WSRC specimens with shear reinforcement is concerned, there is an increase of 8.1%, 26.9%, and 30% is observed in comparison to that of respective PC specimens. However, an over-all decrease in the energies absorbed is observed with the decrease in shear reinforcement from ∅6–64 mm to ∅6–89 mm. The same is in the case of flexural toughness index of WSRC specimens with

Table 5
Flexural strengths, Flexural energies absorbed (FE1, FEM, FEP, FE), and Flexural Toughness Index (FTI) for PC and WSRC beam-lets with varying shear reinforcement and constant flexural reinforcement (i.e. 3-∅6).

Properties	Specimens					
	PC			WSRC		
	∅6–64 mm	∅6–76 mm	∅6–89 mm	∅6–64 mm	∅6–76 mm	∅6–89 mm
(1)	(2)	(3)	(4)	(5)	(6)	(7)
FS (MPa)	36.6	36.0	35.3	38.4	38.2	36.4
FE1 (kN.mm)	101.5	104.1	90.8	118.4	121.8	103.2
FEM (kN.mm)	45.4	33.3	29.8	64.7	60.0	54.3
FEP (kN.mm)	131.6	115.1	99.0	142.3	147.4	125.7
FE (kN.mm)	278.6	252.5	219.7	325.4	329.2	266.1
FTI (–)	2.74	2.43	2.42	2.75	2.70	2.58

shear steel rebars. The flexural toughness indices of WSS1, WSS2, and WSS3 are increased by 0.3%, 11%, and 6.6%, respectively when compared to that of PCS1, PCS2, and PCS3, respectively. An increased toughness index of the specimens with shear reinforcement of ∅6–76 mm is observed, when compared to other considered WSRC matrices. It may be noted that, in general, the flexural properties of WSRC are increased with an increase in shear reinforcement. And overall the WSRC with shear reinforcement (i.e. ∅6–64 mm, ∅6–76 mm, and ∅6–89 mm) and with flexural reinforcement of 3-∅6 again perform very well under the flexural loading.

A clear comparison of FS, FEP, FE, FTI, and Δ of PC and WSRC with varying shear reinforcement (i.e. ∅6–64 mm, ∅6–76 mm, and ∅6–89 mm) and with constant flexural reinforcement (i.e. 3-∅6) is shown in Fig. 10. Overall, all the WSRC specimens along with shear steel rebars are behaved much better than respective PC beam-let specimens. The enhanced flexural strength, the post cracking behavior, and toughness indices of WSRC with shear steel rebars are observed in comparison to PC. As far as the effect of shear reinforcement in WSRC specimens is concerned, decrease in flexural properties with the decrease in shear reinforcement is observed.

4. Discussion

The fibre reinforced concrete can provide effective stress distribution as compared to the plain concrete [55]. Nilson et al. [56] mentioned Whitney's equation (i.e.$Mr = Ts(d - a/2)$, where $Ts = As \times fy$, and $a = A_s \times f_y/0.85 \times fc' \times b$) to calculate the moment capacity of plain concrete. This equation is then modified by [55] for the fibre reinforced concrete and the modified equation which is proposed by Beshara et al. is $M_{F1} = Ts(d - a/2) + T_f\{(t - t_f/2) - a/2\}$. Here, in this modified equation, the fibre's tensile strength in the effective height of equivalent stress in tensile region is added in Nilson's equation. The tensile strength of fibres in Beshara's equation can be calculated by using $T_f = [1.64V_f(l_f/_f)]bt_f$, where, V_f is volume of fibres in concrete, l_f is length of fibres, and $\varnothing_f$ is diameter of fibres. However, the equation proposed by Beshara et al. is modified by the authors of this study in terms of T_f to calculate the effective height of equivalent stress of wheat straw reinforced concrete in tension region. Beshara et al. used combination of volume, length, and diameter of fibres for calculating the tensile strength of FRC. Whereas, in current study, a simplified approach is adopted for tensile strength of WSRC (T_{WSRC}), where $T_{WSRC} = [(MoR_{WSRC} - MoR_{PC})/2] \times b \times t_f)]$ instead of fibre volume and dimensions as in case of Beshara's equation. The modified equation of moment capacity of WSRC comes out to be $M_{WSRC} = Ts(d - a/2) + T_{WSRC}\{(t - t_f/2) - a/2\}$ with usual notations. The logic behind the addition of factored MoR difference of WSRC w.r.t PC is that, when the applied load exceeds the moment capacity of concrete, the cracks start to appear. The crack resistance comes into existence when the crack is propagated up to the steel rebars. However, in case of fibre reinforced concrete, the presence of fibres resists the formation of first crack. In addition to the formation of first crack, the crack propagation phenomenon is also delayed due to the arresting of cracks by fibres. So, in this way, the load carrying capacity of fibre reinforced concrete is increased. Furthermore, once the cracks reach up to the steel rebars/reinforcement, the tensile strength of fibres is also added with the steel rebars for resisting the cracks. The similar type of behavior and increased flexural strength of wheat straw reinforced concrete with steel rebars is observed in the current study.

The comparison of theoretical moment capacities of PC and WSRC with steel rebars from the equation by Nilson et al. and modified equation, respectively, is also made with the respective experimental moment capacities. The theoretical and experimental moment capacities of reinforced concrete and WSRC with steel rebars is given in Table 6. The experimental moment capacity (i.e. M_{Exp}) is calculated by using the area of shear capacities for the respective specimens (i.e. $V_{Exp} \times X$). However, the theoretical moment capacity (i.e. M_r) of plain concrete reinforced with steel rebars is calculated by using Nilson's equation [56]. Whereas, in case of WSRC beam-lets reinforced with steel rebars, the equation proposed by Beshara et al. [55] and modified by the authors of current study, is used for calculation of theoretical moment capacities. For a beam with $f_y = 280MPa$, $d = 76mm$, $f'_{c_{PC}} = 22.5MPa, b = 102mm$, and $A_s = 0.25$, the M_r comes out to be 2836 kN.mm by using the Nilson's equation. The increased moment capacities by WSRC are observed when put in the equation developed for wheat straw reinforced concrete. For a WSRC beam with $f_y = 280MPa$, $d = 76mm$, $f'_{c_{WSRC}} = 21.8MPa$, $b = 102mm$, $t = 102mm$, $t_f = h/2 = 51mm$, $MoR_{WSRC} = 3.42MPa$, $MoR_{PC} = 3.30MPa$ and $A_s = 0.25$, the M_{WSRC} comes out to be 2970 kN.mm by using the Beshara's equation modified for WSRC by the authors. A maximum increase

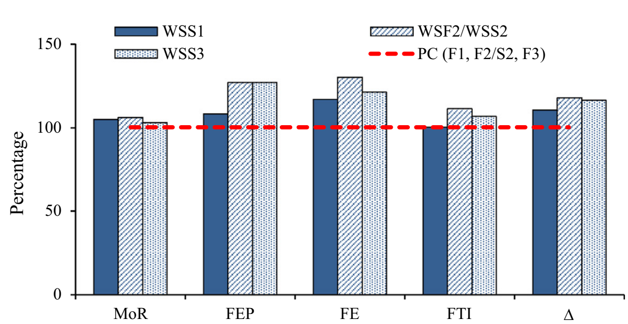

Fig. 10. Comparison of FS, FEP, FE, FTI, and Δ of PC and WSRC with varying shear reinforcement (i.e. ∅6–64 mm, ∅6–76 mm, and ∅6–89 mm) and with constant flexural reinforcement (i.e. 3-∅6).

Table 6
Comparison of theoretical and experimental moment capacities for PC and WSRC with flexural and shear rebars.

Parameter	Unit	Specimens					
		Flexural Rebars			Shear Rebars		
(1)	(2)	2-∅6 (3)	3-∅6 (4)	2 + 2-∅6 (5)	∅6–64 mm (6)	∅6–76 mm (7)	∅6–89 mm (8)
Area of steel (A_s)	in^2	0.20	0.25	0.29	0.25	0.25	0.25
[1]$\boldsymbol{M_r}$ for PC	kN.mm	2436	2836	3286	2836	2836	2836
[4]$\boldsymbol{M_{PC_{Exp}}}$ for PC	kN.mm	3021	3149	3293	3198	3149	3081
[2]$\boldsymbol{M_{WSRC}}$ for WSRC	kN.mm	2670	2970	3407	2970	2970	2970
[4]$\boldsymbol{M_{WSRC_{Exp}}}$ for WSRC	kN.mm	3249	3337	3497	3356	3337	3176

Note: 1. $\mathrm{Mr} = \mathrm{Ts}(\mathrm{d} - a/2)$, where $Ts = As \times fy$, and $a = A_s \times f_y/0.85 \times fc' \times b$.
2. $\mathrm{M_{WSRC}} = \mathrm{Ts}(\mathrm{d} - a/2) + \mathrm{T}_{WSRC}\{(t - t_f/2) - a/2\}$, where $T_{WSRC} = [MoR_{WSRC} - MoR_{PC}/2] \times \mathrm{b} \times t_f$.
3. $f_y = 280\mathrm{MPa},\ d = 76\mathrm{mm},\ f'_{c_{PC}} = 22.5\mathrm{MPa},\ f'_{c_{WSRC}} = 21.8\mathrm{MPa},\ b = 102\mathrm{mm},\ t = 102\mathrm{mm},\ t_f = h/2 = 51\mathrm{mm},\ MoR_{WSRC} = 3.42\mathrm{MPa},\ MoR_{PC} = 3.30\mathrm{MPa}$.
4. $M_{PC_{Exp}} = V_{PC_{Exp}} \times X$ *and* $M_{WSRC_{exp}} = V_{WSRC_{Exp}} \times X$, Where $V_{PC_{Exp}} = L_{m_{PC}}/2$ *and* $V_{WSRC_{Exp}} = L_{m_{WSRC}}/2$, *where* $L_{m_{PC}} \& L_{m_{WSRC}}$, are taken from Tables 2 and 4; and $X = 76\mathrm{mm}$ (Refer to Fig. 3a).

of 9.8% in moment capacity of WSRC (i.e. M_{WSRC}) with flexural reinforcement (i.e. 2-∅6) and shear reinforcement (i.e. ∅6–64 mm) is observed when compared to the moment capacity (M_r) by the respective specimen of reinforced concrete. However, as far as the difference between theoretical and experimental moment capacities is concerned, an overall difference of ±20% is observed.

The experimental shear capacities (V) of PC and WSRC with flexural and shear steel rebars are taken as half of the maximum load as the beam-lets are tested in three-point load test. Whereas, the theoretical shear capacities are determined from the theoretical moment capacities of the respective specimens. The theoretical and experimental shear capacities for PC and WSRC are given in Table 7. Likewise, in moment capacities, the shear capacities for WSRC are also increased when compared to that of RC. A maximum increase of 7.5% is observed in experimental shear capacity of WSRC specimens with shear rebars ($V_{WSRC_{Exp}}$) as compared to the respective reinforced specimens. However, in theoretical shear capacities, the maximum of 9.6% increase in the theoretical shear capacity of WSRC with rebars is observed when compared to the respective specimen of reinforced concrete. Here again, a difference of approximately ±20% is observed in theoretical and experimental shear capacities.

In the rigid pavements, the vehicular load is resisted by the flexural strength of concrete. The steel reinforcement in rigid pavements is not used for carrying load but for controlling the formation of cracks or resisting the propagation of cracks [57]. Conventional concrete pavements are generally classified as jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuous reinforced concrete pavement (CRCP). The addition of straw in the jointed plain concrete pavement can lead to more crack resistance in the pavements. The propagation of cracks in wheat straw reinforced concrete can also be delayed by the help of dispersed straw. Whereas, in case of jointed and continuous reinforced concrete pavement, the incorporation of wheat straw in the concrete along with steel rebars can result in the enhanced flexural strength of concrete which is reported in the current study. This enhanced flexural strength will then result in improved load carrying capacity of jointed/continuous reinforced concrete pavement along with the crack resistance. The incorporation of fibres can also be helpful for steel rebars in resisting the cracks. Hence, the wheat straw reinforced concrete can be concluded in reduction of steel reinforcement.

Huang [58] reported that the basic rigid pavement design equation as per American Association of State Highway and Transportation Officials (AASHTO) 1993: II-45 is used for the design of rigid pavements. The equation is as follows:

$$\log_{10}\mathrm{W}_{18} = \mathrm{Z_R S_o} + 7.35\log_{10}(\mathrm{D}+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta \mathrm{PSI}}{4.5-1.5}\right]}{1 + \frac{1.624\times10^7}{(\mathrm{D}+1)^{8.46}}} + (4.22 - 0.32\rho_t)\left[\frac{\mathrm{S'_c C_d}[\mathrm{D}^{0.75} - 1.132]}{215.63\mathrm{j}\left[\mathrm{D}^{0.75} - \frac{18.42}{\left(\frac{\mathrm{E_c}}{\mathrm{k}}\right)^{0.25}}\right]}\right] \quad (1)$$

where W_{18} = Traffic load in equivalent standard axle loads; $\mathrm{Z_R}$ = Standard normal deviation for desired reliability; $\mathrm{S_O}$ = Overall standard deviation; D = Slab thickness (in); ΔPSI = Serviceability index; $\mathrm{S'_c}$ = Flexural strength of concrete (psi); $\mathrm{C_d}$ = Drainage coefficient; J = Load transfer coefficient; $\mathrm{E_c}$ = Elastic modulus of concrete (psi); and k = subgrade reaction modulus (psi/in).

However, in case of WSRC specimens with the steel rebars, the flexural strengths are increased as compared to that of PC. The flexural strengths of PC and WSRC with flexural and shear rebars along with the increment factor of WSRC w.r.t PC are given in Table 8. The flexural strengths of WSRC specimens, with steel reinforcement 2-∅6, 3-∅6, 2 + 2-∅6, ∅6–64 mm, ∅6–76 mm, and

Table 7
Comparison of theoretical and experimental shear capacities for PC and WSRC with flexural and shear rebars.

Shear Capacities			Specimens					
			Flexural Rebars			Shear Rebars		
Symbol (1)	Formula* (2)	Unit (3)	2-∅6 (4)	3-∅6 (5)	2 + 2-∅6 (6)	∅6–64 mm (7)	∅6–76 mm (8)	∅6–89 mm (9)
$\boldsymbol{V_{PC_{Theo}}}$	$V_{PC_{Theo}} = M_{PC_{Theo}}/X$	kN	32.0	37.2	43.1	37.2	37.2	37.2
$\boldsymbol{V_{PC_{Exp}}}$	$V_{PC_{Exp}} = L_{m_{PC}}/2$	kN	39.7	41.3	43.2	42.0	41.3	40.4
$\boldsymbol{V_{WSRC_{Theo}}}$	$V_{WSRC_{Theo}} = M_{WSRC_{Theo}}/X$	kN	35.0	39.0	44.8	39.0	39.0	39.0
$\boldsymbol{V_{WSRC_{Exp}}}$	$V_{WSRC_{Exp}} = L_{m_{WSRC}}/2$	kN	42.6	43.9	45.9	44.1	43.9	41.7

*Note: 1. $M_{PC_{Theo}}$ & $M_{WSRC_{Theo}}$ is taken from Table 6, and X = 76mm (Refer to Fig. 3a).
2. $L_{m_{PC}}$ & $L_{m_{WSRC}}$ is taken from Tables 2 and 4.

Table 8
Increased flexural strengths of WSRC specimens w.r.t PC specimens.

Flexural Strengths	Specimens					
	Flexural Rebars			Shear Rebars		
	2-∅6	3-∅6	2 + 2-∅6	∅6–64 mm	∅6–76 mm	∅6–89 mm
(1)	(2)	(3)	(4)	(5)	(6)	(7)
FS_{PC} (MPa)	34.6	36.0	37.7	36.6	36.0	35.3
FS_{WSRC} (MPa)	37.2	38.2	40.1	38.4	38.2	36.4
Increment Factor (FS_{WSRC}/FS_{PC})	1.08	1.06	1.05	1.05	1.06	1.03

∅6–89 mm, are increased by a factor of 1.08, 1.05, 1.06, 1.05, 1.05, and 1.03, respectively, when compared to that of respective PC specimens. The average increment in WSRC with respect to PC comes out to be 1.05. Therefore, to cater the effect of tensile stresses induced at bottom of pavement surface due to the applied traffic loading, the added strength of straw in case of WSRC pavements can be accounted by simply modify the above mentioned AASHTO equation by using the increment factor of flexural strength. Hence, the S'_c in the equation is modified for the flexural strength of WSRC for incorporating the effect of tensile strength due to addition of wheat straw and is as follows:

$$S'_{WSRC} = MoR_{WSRC} \times 1.05 \tag{2}$$

where 1.05 is the averaged increment factor in flexural strength of WSRC. The modified pavement slab thickness design equation with the incorporation of S'_{WSRC} will become as follows:

$$\log_{10}W_{18} = Z_R S_o + 7.35\log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624\times10^7}{(D+1)^{8.46}}} + (4.22 - 0.32\rho_t)\left[\frac{S'_{WSRC}C_d\left[D^{0.75}-1.132\right]}{215.63j\left[D^{0.75}-\frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right]}\right] \tag{3}$$

As per Portland Cement Association and AASHTO design methods for rigid pavements, the same method is used for continuous reinforced concrete pavement as used for jointed plain and reinforced concrete pavement. The only difference that can be occurred in the thickness design of continuous reinforced concrete pavement and conventional concrete pavement is in the load transfer coefficient. As in case of continuous reinforced concrete pavement, the value of load transfer coefficient can be reduced from 8 cm to 7.4 cm. Which will cause the reduction in slab thickness of 2 cm. However, the deflections and critical stresses in continuous reinforced concrete pavement are more or less same as in case of jointed plain/reinforced concrete pavement. Therefore, it is recommended that same thickness should be used. So, the above-mentioned equations are solved for PC and WSRC specimens to calculate the thickness of PC and WSRC pavement, respectively. The solved thickness is compared with solved design example of AASHTO 1993: II-45. For PC and WSRC specimens, all the design parameters (i.e. given in Table 9) are kept constant as taken in the example which is done in AASHTO 1993: II-45 except the concrete material properties i.e. flexural strength (S'_c) and modulus of elasticity (E_c). The variation in the concrete pavement slab thickness of PC and WSRC specimens in comparison with the solved AASHTO 1993: II-45 equation is given in Table 10. Considering the modified equation to account the effect of straw, the WSRC pavement thickness is reduced by 7% as compared to that of PC. In addition to that, due to the addition of straw in concrete, the bridging mechanism occurs which enhance the energy absorption of WSRC by resisting the crack formation. This bridging/sewing effect is due to the relatively better bond of straw with surrounded concrete matrix because of the rough surface of straw after pre-treatment. Furthermore, once the cracks are formed, the crack width and crack propagation under the traffic loading is also restricted and delayed, respectively, due to the crack arresting mechanism which occurs with incorporation of straw. In short, the improved post-cracking behavior can be achieved in WSRC pavements with 7% less thickness as for PC. As far as the continuous reinforced concrete pavement is concerned, the incorporation of straw in addition to the steel rebars/reinforcement, can lead towards increased flexural strengths along with the better post cracking behavior. Because, in this scenario, the added flexural strength, due to the incorporation of fibres, in the flexural strength of concrete will provide more crack resistance. The increased flexural strengths of WSRC with steel rebars are also reported in the current study. In case of cracks occurrence, the time period for the cracks to propagate up to the steel rebars will be enhanced due to crack arresting by straw in the concrete cover. And, in the worst condition, when the cracks reach up to the steel rebars, the straw will also be enriching the crack resisting capability of steel rebars as can be observed in Figs. 5 and 9. The whole phenomenon will ultimately be counting towards resisting punch-outs in WSRC concrete pavements. The percentage area of steel can also be reduced by some percentage of added flexural strength

Table 9
Design parameters for 1998 AASHTO rigid pavement design model.

Parameter (1)	Value (2)
Equivalent Standard Axle Loads (W_{18})	5100000
Reliability (R)	95%
Standard Deviation (S_o)	0.30
Elastic Modulus of Concrete (E_c)	Variable (psi)
Flexural Strength of Concrete (S'_c)	Variable (psi)
Poisson's ratio of Concrete (μ)	0.15
Seasonal k-value (k)	72 psi/in
Initial serviceability (p_i)	4.2
Terminal serviceability (p_t)	2.5

Table 10
Comparison of pavement thicknesses against flexural strength and modulus of elasticity for PC and WSRC.

Specimens (1)	Flexural Strength (S'_c) (MPa) (2)	Modulus of Elasticity (E_C) (MPa) (3)	Pavement Slab Thickness (cm) (4)	Remarks (5)
JRCP	4.50	34,474	25	AASHTO-93 II-45
PC	3.30	19,445	29	Current Study
WSRC	3.59	18,742	27	

of straw. This will reduce the quantity of steel reinforcement to be used in continuous reinforced concrete pavement. Thus, ultimately will be resulting in reducing the overall cost of pavement.

5. Conclusions

The plant fibre (i.e. wheat straw) in concrete with flexural and shear reinforcement are investigated in this experimental study. Straw of 1% content, by mass of wet concrete, and length of 25 mm are added in the same mix (i.e. 1:2:4) as for PC. The contribution of plant fibre (i.e. wheat straw) is studied for improving the capacities and behavior of concrete reinforced with flexural and shear steel rebars for its use in concrete pavements. Plain Concrete (PC), and Wheat Straw Reinforced Concrete (WSRC) with the flexural and shear reinforcement are studied. In addition to this, the moment capacity design equation and concrete pavement thickness design equation are also proposed. The conclusions are as follows:

- A maximum load increase of 7% in the first crack initiation is observed for WSRC with flexural rebars as compared to that of PC. And the maximum load is increased by 7.6% in comparison to PC. In WSRC, the number of cracks, crack widths, and crack lengths are decreased up to 25%, 140% and 66%, respectively, when compared to the respective PC specimens.
- WSRC with flexural reinforcement show enhancement up to 7.5%, 44.8%, 30.4%, and 11.7% in FS, FEP, FE, and FTI, respectively, as compared to the respective PC beam-lets. The moment capacities of WSRC with flexural and shear rebars are increased up to 2.8% and 2%, respectively, in comparison to that of PC.
- As far as the WSRC specimens with shear rebars are considered, the maximum increases of 6.9% and 7% in first crack and ultimate loads, respectively, are observed when compared to the respective loads of PC specimens with shear rebars. Here again, the severity of cracks in terms of quantity, width, and length are decreased up to 20%, 75% and 50%, respectively, in WSRC specimens as compared to respective PC specimens.
- Increase in FS, FEP, FE, and FTI of WSRC with shear steel rebars are up to 6%, 27%, 30.1%, and 11.2% w.r.t that of respective PC specimens. Shear capacities of WSRC specimens with flexural and shear rebars are increased up to 7.3% and 6.3%, respectively, in comparison to that of respective PC specimen.
- The pavement slab thickness is decreased by 7% for WSRC as compared to PC for same load parameters. In addition to that, the improved behavior, delay in first crack initiation, more resistance in crack propagation and better post-cracking behavior of WSRC is observed which is favorable under traffic loading.

So, based on the conducted research, it can be claimed that the WSRC with steel rebars is likely to have the potential to be used for concrete pavement applications. Also, the proposed equations for moment capacity and concrete pavement thickness design can be applicable for wheat straw reinforced concrete. However, it's durability and the performance of WSRC road panels are recommended to be explored in detail.

Conflict of interests

The authors declare no conflict of interests.

Acknowledgements

The authors would like to acknowledge all the persons/organization who supported them in this research program, particularly Engr. Mehran Khan, Engr. Faheem Gul, Engr. Tassadaq Hussain, and Mr. Muhammad Saqib for their kind support during the lab work and research. The authors would also like to acknowledge the anonymous reviewers for the careful review and suggestions for the improvement.

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