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Improving performance of light weight concrete with brick chips using low cost steel wire fiber

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HIGHLIGHTS

- GI wire fiber can be used as a low-cost alternative to steel fibers in concrete.
- Optimum GI fiber content is 2–2.5% by weight for conventional brick chip concrete.
- Considerable cost saving can be achieved by using GI fiber instead of steel fiber.

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ABSTRACT

Brick chips, produced from burnt clay, are quite common in Bangladesh and other countries of the south-east region of Asia and have been used as coarse aggregate for many years. These brick chips are considered as light weight aggregate (LWA) because of their light weight and porous structure. Brick chips concrete is a form of light weight aggregate concrete (LWAC) and has lower mechanical properties and higher brittleness than conventional normal weight concrete. Improving this aspect of LWAC with brick chips is of great importance since brick chips are very popular in the country due to low cost and wide availability. Therefore, a comprehensive investigation has been made in this study on the improvement of strength and ductility of concrete having brick chips as coarse aggregate using locally produced low cost lightly galvanized mild steel wire fiber (commonly known as GI wire fiber in this region) as an alternative to conventional steel fibers. Steel fibers are not available in local markets in many countries of this region such as Bangladesh and importing is quite expensive. Compressive and splitting tensile strength of test cylinders as well as load–deflection and cracking behavior of test beams with variable fiber contents have been evaluated. Marked improvement has been noticed for compressive and tensile strength of concrete through GI wire fibers addition. Ultimate strength and toughness showed maximum increment up to thirty percent for a certain range of fiber content. Moreover, fiber inclusion has enhanced resistance against crack formation and propagation which is evident from crack width, crack spacing with respect to loads applied and crack patterns. Results of the experiments and cost comparison reveal that GI fiber can be adopted as a viable low cost alternative to steel fibers for performance enhancement of brick chips concrete.

1. Introduction

Concrete is the most widely used construction material throughout the globe. Especially in the developing regions of the world, construction of infrastructure constitutes the major share of the total development work. And concrete is an indispensible part of these development works in countries like Bangladesh as ingredients of concrete is inexpensive, readily available as well as concrete work is relatively simple to execute and maintenance free. However, the major limitation of concrete is the lack of ductility. In Bangladesh, this limitation is even more pronounced due to poor construction practice and lack of quality control. In addition to that, a vast region of the country falls in an active seismic zone which calls for the structures to be more resilient and ductile. Furthermore, extensive use of brick chips (crushed burnt clay bricks), which is a form of light weight aggregate (LWA), as coarse aggregate in concrete in this south-east region of Asia has posed some additional concerns to ponder; as light weight aggregate con-

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crete (LWAC) is expected to have higher brittleness and lower mechanical properties than normal weight concrete (NWC) [1]. Therefore, improving this aspect of LWAC with brick chips has the prime focus of the civil engineers and researchers.

Considerable number of studies have been carried out by incorporating various types of fibers such as steel fiber, glass fiber, fiber polymer, natural fiber, and nano-fiber within cement mortar and concrete [2–7]. Concrete with these fibers, generally known as FRC (fiber reinforced concrete), has improved ductility, better flexural performance and energy absorption capacity [8–10]. In the field of FRC, steel fiber is, by far, the front runner as a suitable reinforcing material [4,11]. Performance of steel fiber in concrete to improve mechanical properties, such as tensile strength, ductility, toughness, fatigue life, and impact resistance has been well established [8,9,12,13]. Majority of the previous researches in FRC have been conducted for concrete with normal weight aggregate like stone chips as coarse aggregate. A number of literatures are also available for fiber-reinforcing in various LWAC where pumice, oil palm shell etc. have been utilized as LWA [1,14,15]. However, a thorough literature review fails to reveal any significant study on FRC with brick chips aggregate. There are no authentic research results or database to comprehend the behavior of FRC produced from brick aggregate. However, in this region, brick chips are used massively in concrete works due to ease of availability and relative low cost. Therefore, performance enhancement of concrete made with brick chips needs an exclusive attention since use of brick chips as coarse aggregate is very popular particularly for construction of beams and slabs. Undoubtedly, use of steel fiber could be a promising solution to relative poor performance of brick chips concrete. Thus, a thorough investigation on performance of brick chips concrete reinforced with suitable fibers is of immense importance. A major constraint of using steel fiber in a country like Bangladesh is its relative high cost. Such additional cost for steel fibers can be an issue in popularizing them. In this context, fibers from locally manufactured lightly galvanized mild steel wire, popularly known as GI (Galvanized Iron) wire, can provide a viable low cost alternative to steel fibers, especially for Bangladesh and other developing countries [16]. Steel fiber for use in FRC is not available in local markets in many of these countries and importing can be quite expensive. Moreover, GI wire is locally produced and is available at a relatively low price.

GI wire fiber is different from conventional steel fiber in both shapes and properties. Steel fibers are available in various shapes and strengths, but GI wire fiber is normally straight cut from wires. GI fiber is relatively low in strength and more flexible as compared to typical steel fibers [16]. Research with GI wire as a suitable concrete reinforcing material is in the budding phase and behavior of GI Fiber Reinforced Concrete (GFRC) is yet to be properly investigated. With this as backdrop, experiments were conducted with GFRC with an aim to comparing performance of GI wire fiber as an alternative to steel fiber in concrete with brick chips as coarse aggregate. Concrete with crushed stone chips were also made for comparison. Compressive, splitting tensile and flexural strength of GFRC has been investigated. The experiments exhibited promising results when compared with steel fiber reinforced LWAC. A cost comparison also reveals that GI fiber can be a good option of cutting the cost of steel fiber in Bangladesh.

2. Background

It is now well established that adding discrete, randomly distributed steel fibers can improve concrete mechanical properties, such as tensile strength, toughness, durability, fatigue life, and impact resistance [9,15,17–22]. The composite material resulted from incorporation of steel fiber within concrete is commonly known as steel fiber reinforced concrete (SFRC). Because of its enhanced tensile strength and toughness in compression, SFRC has great potential for use in construction industries. The American Concrete Institute is also gradually promoting SFRC in building structural applications by including it in their Codes [23]. Fiber content and attributes usually do not have direct influence on compressive strength properties of fiber reinforced concrete; nonetheless, they can passively contribute to augmentation of compressive strength [18,19,24]. This phenomenon can be attributed to the confining effect of fibers and the countering effect to the lateral tension. Fibers aligned with tensile stresses may result in large increases in direct tensile strength, as high as 133% for 5% of smooth/straight steel fibers [25]. However, it has been observed that increase in tensile strength is quite variable since this enhancement depends on various factors like dispersion and alignment of fibers, fiber fraction, aggregate type, mix proportion etc. For randomly distributed fibers, the increase in strength can be much smaller. One major advantage of steel fibers is that steel fiber reinforcement can lead to significant increases in the post-cracking behavior or toughness of the composites [4,10,26]. Moreover, it has been found that fiber reinforcing reduces both potential of cracking and crack width, especially in early hydration stages [27,28]. As a result of reduced crack propagation, SFRC is known to have much better durability compared to concrete without fiber [29].

The history of research on modern SFRC stretches back to early 1960s [3]. Since initiation, majority of studies for many years were confined to the investigation of plain SFRC beams without main steel reinforcement. Investigation on the effects of fiber reinforcement on conventional reinforced concrete members eventually followed [30–32]. Oh [20] studied the mechanical behavior of reinforced concrete beams containing steel fibers. The steel fiber content varied from 0% to 2% by volume (0–7% by wt.). Generally, fiber reinforced composites are categorized according to fiber content into three classes such as low (below 1% vol. fraction), moderate (1–2% vol. fraction) and high (above 2% vol. fraction). The study by Oh [20] found marked increase in flexural strength and ductility and also reported significant improvement in crack control in SFRC when used alongside main reinforcement. It has also been shown that steel fibers effectively reduce the bursting pressures in the anchorage zones of post-tensioned concrete bridge members and reduce the need for secondary reinforcements, resulting in less steel congestion and improved constructability [33]. The ACI 318 Building Code has introduced steel fibers in shear design provisions, allowing the elimination of minimum shear reinforcement in SFRC (ACI [23]). Later on effect of steel fiber reinforcement has been investigated for various other types of concrete like concrete with different types of light weight aggregate (LWA), high performance concrete etc. Although researchers observed performance augmentation in most of the cases, the degree of enhancement has been found different for concrete having different types of LWA. For example, SFRC, with 0.5% volume fraction (1.7% by weight) of steel fiber and having oil palm shell, pumice and expanded clay as LWA, experienced compressive strength increment of 8% [34], 8% [35] and 18% [36], respectively. Again, with 1% volume content (3.4% by weight) of steel fiber for the same three types of aggregates, improvement in compressive strength was about 18% [34], 11% [35] and 27% [36], respectively. It is, therefore, evident that a comprehensive investigation is necessary before recommending fiber reinforcement for concrete having a new type of LWA. Since, fiber reinforcing technique is yet to be comprehensively applied on brick aggregate concrete as a LWAC, the present study can be considered as the initial progress in this context. Moreover, GI wire fiber as a substitute of conventional steel fiber is another aspect that makes this study distinctive.

3. Experimental program

The objective of the experiments conducted herein was to assess the performance of GFRC as fiber reinforced LWAC, in the form of compressive/tensile strengths and ductility. For ductility evaluation, flexural analysis and load–deflection behavior of test specimens were studied to determine various parameters, such as first cracking load, ultimate load, deflection and crack patterns at various loading stages, and toughness. The following experiments were performed:

– Compressive strength of cylindrical concrete specimens.
– Splitting tensile strength of cylindrical concrete specimens.
– Flexural/ductility analysis of reinforced concrete beams.

3.1. Test materials

3.1.1. GI wire fiber

GI wire of 0.7 mm (0.03 in.) diameter was chosen and suitable length for the wire was taken to be 37.5 mm (1.5 in) [20]. The resulting aspect ratio of 54 falls within the limit of 30–100 as specified in different codes and standards (ACI 544.3R [37], ASTM A820/A820M [38]). Fiber content was varied from 1 to 3.5% by weight in order to keep the fiber content low enough to maintain workability without admixture. Average yield and ultimate strengths of the wire were measured as 340 MPa (49ksi) and 500 MPa (72.5ksi), respectively. Typical stress–strain curve of GI wire from laboratory testing is shown in Fig. 1.

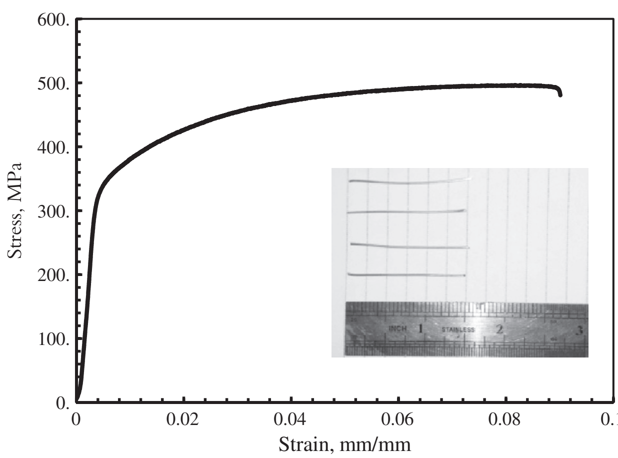

Fig. 1. Typical Stress–strain curve for GI wire from testing (Inset: GI wire fiber).

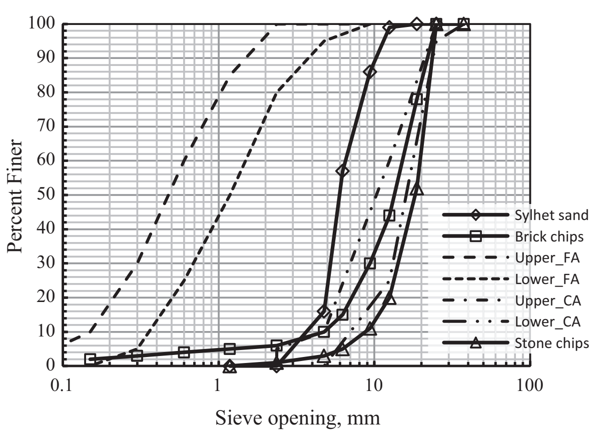

Fig. 2. Gradation curve of coarse and fine aggregates.

3.1.2. Concrete

Ordinary Portland cement was used with 19 mm (¾ in.) downgraded crushed burnt clay bricks and stone chips as coarse aggregate and locally available Sylhet sand (Fineness Modulus = 2.42) as fine aggregate. Oven-dry rodded unit weight and absorption capacity of brick aggregate was found to be 1040 kg/m^3 and 14.3%, respectively. Gradation curves from sieve analysis for brick chips, stone chips and fine aggregates are presented in Fig. 2. Grading limits as specified in ASTM C 33 are also shown in the figure and it is evident that the coarse aggregate perfectly falls within the range but the fine aggregate is coarser than the range stipulated. Nevertheless, due to all pervasive use of the sand in this region, it was used in the experiments as fine aggregate. In Bangladesh, a majority of construction work is dependent on small scale mixing and casting methods, where concrete mix is proportioned with a conventional volumetric ratio of 1:1.5:3 for cement, fine aggregate and coarse aggregate, respectively. This mix-design was adopted for the study. Commonly practiced water/cement ratio of 0.45 was used without any superplasticizer. The target strength was selected as 18 MPa (2500 psi) considering the typical lower bound design strength of beams and slabs in this region.

Addition of GI fiber reduced slump value of concrete mix as expected from previous works with various other types of fibers [39,40]. According to Mehta and Monteiro [4], a slump of 50 mm is enough for LWAC, but all the GFRC mixes have slump value under this limit. But traditional slump test does not give a fair indication of workability of fiber reinforced concrete [10,39] and even, FRC with a zero slump can be workable enough for proper compaction [1]. Similar phenomenon was also experienced in the present study where compaction was performed with a vibrator and the workability was found to be moderately satisfactory. Mix proportion on weight basis and corresponding slump values are presented in Table 1.

3.1.3. Steel reinforcements

For the construction of test beams, conventional main reinforcements in the form of longitudinal reinforcement and stirrups were provided along with GI wire fibers. Yield and ultimate strength of the steel was found to be 524 MPa (74.5 ksi) and 592 MPa (85.8 ksi), respectively. Average elongation was around 20% at rupture.

3.2. Design and fabrication of test members

Rectangular reinforced concrete beams, with seven separate mix-proportions, including one control mix (without any GI wire) and six mixes (with different fraction of GI wire) with brick chips as coarse aggregate, were designed in accordance with ACI provisions [23]. Two more mixes were done with stone chips and GI wire fiber to compare the results with previous studies. Each beam was 150 mm (6 in.) wide, 200 mm (8 in.) deep, with an effective depth to the steel centroid of 169 mm (6.76 in.) and d' = 31 mm (1.24 in.). The effective span length for the test beams was 1.35 m (54 in.). Some minor adjustments to the code requirements were made for concrete cover issues because of the small beam dimensions.

The beams were reinforced with longitudinal reinforcement at the bottom and two binder rods were placed at the top. Minimum and maximum ACI permitted reinforcement ratios for the beams were found to be 0.0028 and 0.015, respectively. Two Ø10 mm (#3) bars were provided at bottom, which furnished 36% of the maximum reinforcement ratio. To avoid premature shear failure of the beams during loading and handling and to ensure a flexural failure, Ø8 mm (#2) two-leg vertical stirrups were provided with 150 mm (6 in.) center to center spacing throughout the span. Details of the beam fabrication and design are illustrated in Fig. 3.

3.3. Testing methodology

The beams were subjected to third point loading as shown in Fig. 3. The beams were mounted on a platform and two steel blocks with semi-circular upper end were placed at the bottom at the points of support so that the beam can deflect as a simply supported beam. Loads were applied at each of the third points by a Tinius Olsen Universal Testing Machine. A constant deflection-controlled loading was applied with the movement rate of the platform being 5 mm/min. Time versus

Table 1
Mix proportions and slump values of test concrete.

Concrete	Ingredients	Control	GFRC-1	GFRC-1.5	GFRC-2	GFRC-2.5	GFRC-3	GFRC-3.5
Mix proportions	Cement, kg/m^3	153	153	153	153	153	153	153
	CA, kg/m^3	389	389	389	389	389	389	389
	FA, kg/m^3	260	260	260	260	260	260	260
	Fiber, wt.%	0	1	1.5	2	2.5	3	3.5
	(vol.%)	(0)	(0.29)	(0.44)	(0.58)	(0.73)	(0.87)	(1.02)
Slump (mm)	–	50	40	28	16	8	0	0

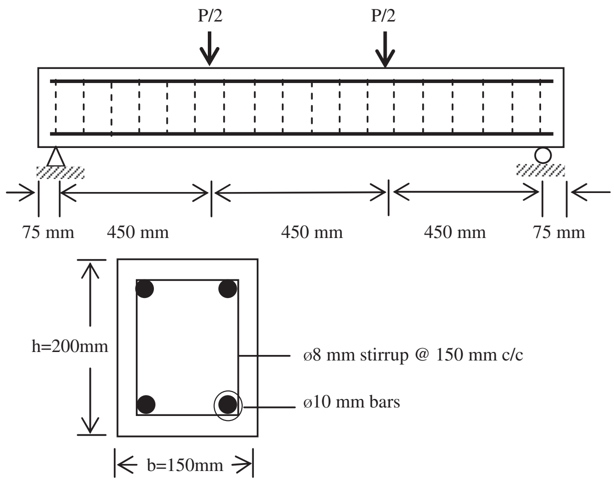

Fig. 3. Schematic diagram for details of test beams.

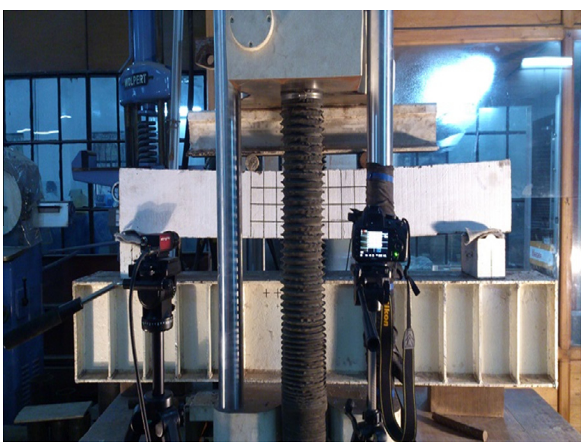

Fig. 4. Test setup for beam flexure.

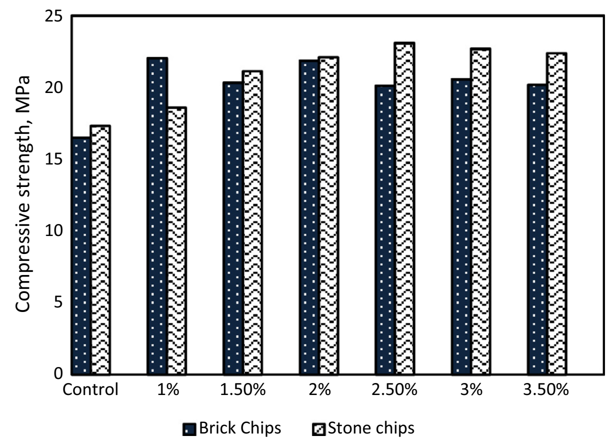

Fig. 5. Compressive strength of normal concrete and GFRC.

load was continuously monitored and data was saved through a data logger. Deflection and cracks of the beam were monitored with a video extensometer continuously. Change of deflection and crack width with time was measured by methods of Digital Image Correlation (DIC). Fig. 4 displays the overall setup for beam testing.

4. Results and discussion

The compressive strengths of various control and GFRC test cylinders were determined according to ASTM standard (ASTM C39/C39M-14a) [41]. Three samples per each concrete mix were tested. Individual results have been presented in Table 2 and average results are shown in Fig. 5. Both brick chip and stone chip concrete exhibited increment in strength due to fiber addition but no definite relationship between strength and fiber content can be drawn. A maximum increase of 33% was observed for both stone and brick chip concrete. Campione et al. [36] found that steel fiber addition of 0.5% and 1% by volume fraction (1.7% and 3.4% weight fraction) increased compressive strength by 22% and 29%, respectively for monotonic loading for LWAC with expanded clay. Moreover, other works on steel fiber incorporation in LWAC reported

Table 2
Results of compressive strength and splitting tensile strength test.

	Compressive strength, MPa				Splitting tensile strength, MPa			
	Brick chips		Stone chips		Brick chips		Stone chips	
	Individual	Average	Individual	Average	Individual	Average	Individual	Average
Control	16.53	16.53	18.34	17.33	1.68	1.79	2.33	1.97
	18.02		16.02		1.62		1.81	
	15.03		17.62		2.05		1.78	
1% GFRC	23.13	16.53	18.52	18.60	2.24	2.16	1.68	2.36
	22.39		19.18		2.30		2.77	
	20.64		18.11		1.93		2.62	
1.5% GFRC	21.14	20.35	22.20	21.14	2.67	2.57	2.75	2.60
	19.77		21.10		2.49		2.45	
	20.14		20.12		2.55		2.62	
2% GFRC	24.01	21.89	21.40	22.12	2.49	2.40	3.22	3.03
	20.27		23.35		2.55		2.73	
	21.39		21.61		2.18		3.12	
2.5% GFRC	19.02	20.14	23.97	23.11	2.67	2.47	3.01	2.94
	20.77		23.35		2.49		3.01	
	20.64		22.02		2.24		2.82	
3.0% GFRC	20.08	20.62	23.04	22.62	2.68	2.53	3.35	3.47
	21.47		22.84		2.55		3.45	
	20.31		21.99		2.35		3.61	
3.5% GFRC	19.52	20.25	20.84	22.42	2.44	2.44	3.01	2.93
	20.17		24.27		2.51		2.85	
	21.05		22.14		2.36		2.92	

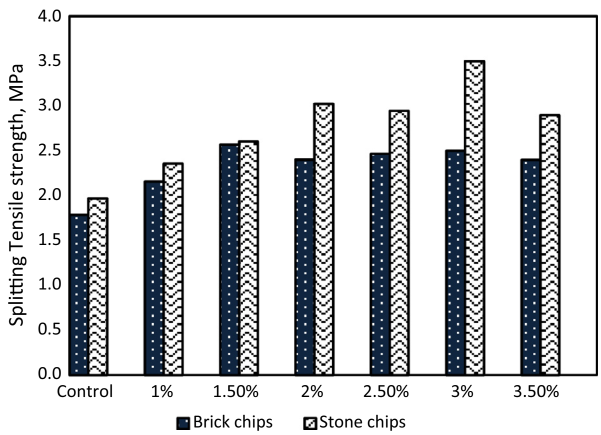

Fig. 6. Splitting tensile strength of normal concrete and GFRC.

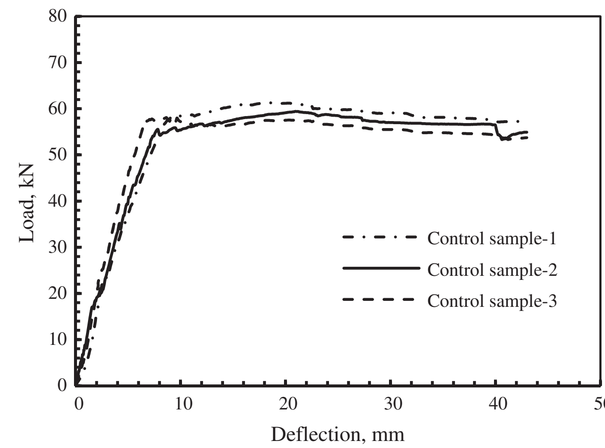

Fig. 7. Load–deflection curve for control samples (BC).

compressive strength increment up to 30% [42], 22% [43], 21% [35] and 20% [44] with good workability. Thus, the results from the current experiment with GI wire fiber is comparable and even better regarding the previous results with conventional steel fiber.

Split tensile strengths of control concrete and GFRC were determined at 28 days according to ASTM standard (ASTM C496/C496M-11) [45]. Fig. 6 presents the results from the tests. A maximum increase of 53% is observed for stone chips concrete and 44% for brick chip concrete (LWAC). From previous studies [14,35,36,43,46] it is found that addition of very low ($V_f \leqslant 0.5\%$) and low ($0.5\% < V_f \leqslant 1\%$) volume fraction of steel fiber in LWAC can provide a maximum increase of 16–61% and 19–116%, respectively.

The beams were tested as described in Section 2.3. A test matrix is provided in Table 3. The load deflection curves derived from the tests for brick chips concrete are presented in Figs. 7–11. Mean load deflection curve for different concrete mixes is shown in Fig. 12 for comparison of performances of GFRC with respect to control concrete. Table 4 summarizes the test results. Several terms used in the table are explained below.

Micro-crack means the very first initiation of cracking which is noted by a sudden small decrease in loading where the load was supposed to steadily rise in the elastic zone. Macro-crack is the initiation of sudden widening of cracks without much increase in load. The load corresponding to the macro-crack is the “macro-crack load”. Micro-crack and macro-crack loads were determined from the recorded continuous load–deflection data and corresponding load–deflection curves. Toughness calculated up to macro-cracking point is the macro-crack toughness. Toughness was calculated by integrating continuous load–deflection data from the data logger using trapezoidal rule of numerical integration. Ultimate strength is the maximum load recorded.

Load–deflection curves under flexural loading are generally utilized to assess flexural capacity as well as ductility and toughness. Load–deflection curves in Figs. 7–11 demonstrate that all the curves for the same fiber content are almost identical, which implies that randomness of fiber dispersion did not vary the result significantly. Therefore, results can be assumed to be reliable since close results were obtained for all tested samples in each set. The form of each load–deflection curve is similar, with a linear elastic

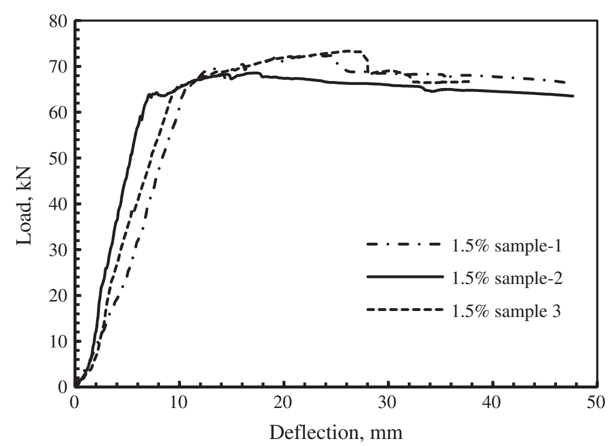

Fig. 8. Load–deflection curve for 1.5% GFRC (BC) samples.

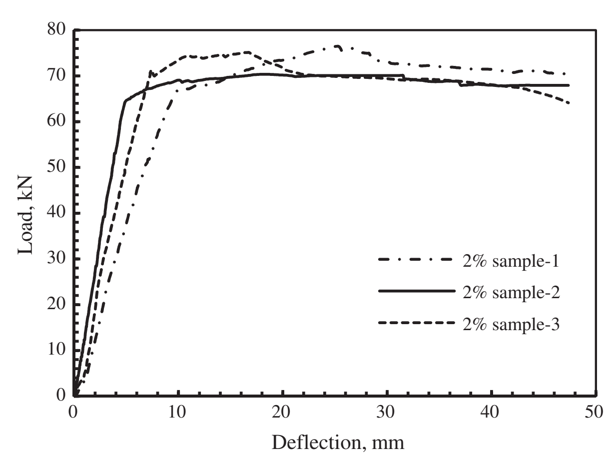

Fig. 9. Load–deflection curve for 2% GFRC (BC) samples.

Table 3
Test matrix.

Concrete	Control	1% GFRC	1.5% GFRC	2% GFRC	2.5% GFRC	3% GFRC	3.5% GFRC	3% GFRC	3.5% GFRC
Coarse aggregate	BC	BC	BC	BC	BC	BC	BC	SC	SC
No of samples	3	3	3	3	3	2	2	2	2

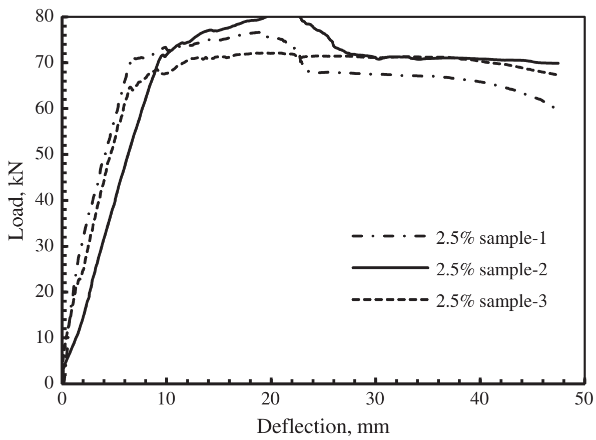

Fig. 10. Load–deflection curve for 2.5% GFRC (BC) samples.

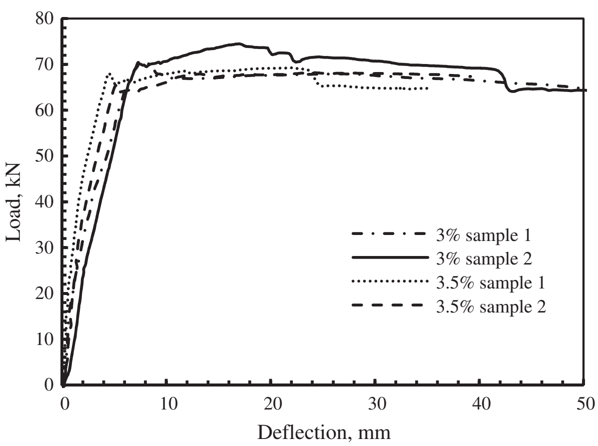

Fig. 11. Load–deflection curve for 3 & 3.5% GFRC (BC) samples.

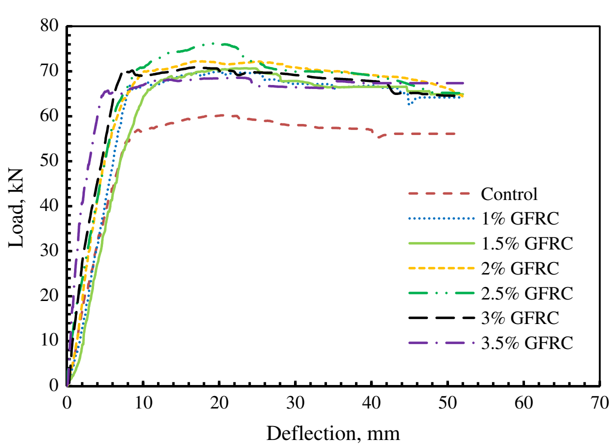

Fig. 12. Average curves for seven different mix-designs (BC).

portion prior to crack formation followed by a plastic deformation region. Fig. 12 clearly shows that addition of GI wire fiber increased capacities of the beams, but the fiber effect is not very discernible as all the curves lie in a very close range. However, 2–2.5% GFRC curves seem to reach higher values than others and therefore give an impression that this range of fiber content performs relatively better. In addition to this, it is observed that the curves of GFRC have considerably steeper slopes than that of control concrete which indicates higher stiffness of GFRC. This is due to the fact that after formation of micro cracks in the tension zone, wire fibers continue to transfer loads across the cracks and enhance both stiffness and flexural capacity. Table 4 clearly shows increments in macro-crack strength, toughness and ultimate strengths. GFRC curves also show slight strain hardening up to a certain strain, which is absent in the control samples. Furthermore, predicted ultimate load is shown in Table 4 in order to compare with the experimental results. Linear regression formula proposed by Rjoub [47] was adopted for the prediction of the response. Experimental results showed better strength compared to predicted strength and such difference between experimental and predicted strength is found to be comparable with results from previous comparative studies [47–49].

To further understand the contribution of fibers, increases in various parameters with respect to control samples are plotted in Fig. 13. Best fit second degree curves were chosen to represent the trends (corresponding R values are provided with the graphs). It is evident that macro-crack and ultimate strength increments peak for fiber content of 2–2.5%, whereas the toughness increment peaks in the 1.5–2% fiber content range.

Changes in crack spacing and width were also studied. Load vs. crack width results are plotted in Fig. 14 which gives a clear idea about the effectiveness of fibers in reducing crack width. The curve for the control sample is located below all the GFRC curves, which indicates that fiber addition deterred crack growth. It is also apparent that fiber content of 1.5–2.5% performed better than other mixes in controlling crack width. Curves of 3% and 3.5% GFRC lie closely below the bundle and not shown in the figure for clarity.

For simplicity of construction and representing actual construction practices, no plasticizer was used. And therefore, concrete placement and compaction became increasingly difficult due to decreased workability in mixes with higher fiber content. This affected various performances of GFRC concrete with higher fiber contents like 3% and 3.5%. Fig. 15 shows average crack spacing vs. load graphs. It is clear that the curves for GFRC samples are above that of the control sample up to about 50 kN load. This indicates that for this range of loading, crack formation for GFRC is less than control samples since spacing of cracks are larger. For loads beyond about 50 kN, there will usually be plastic deformation and excessive cracking. And hence, energy absorption rather than crack spacing for loads in excess of this range of loading is of more significance.

Crack pattern of the samples were also observed. Fig. 16 shows the crack patterns of the specimens when the load is close to the ultimate load. It is obvious that number of cracks reduced with increasing fiber content. The interesting aspect of the crack patterns is that with increasing fiber content, diagonal shear-flexure cracks tend to disappear. For the control specimen, the most prominent cracks are the diagonal shear-flexure cracks near the supports although flexural cracks near mid-span are also present. For specimens with 1 and 1.5% fiber contents, both flexural and diagonal cracks are manifested; but, flexural cracks close to mid-span become the wider cracks as opposed to the cracks of the control sample.

For 2%, 2.5% and 3% fiber contents, diagonal cracks are gradually rendered absent and failure is predominantly governed by flexural cracks. This intriguing phenomenon can be ascribed to the fact that fiber reinforcement adds to the shear strength of concrete as pointed out in ACI 318 [23]. Failure modes presented in Table 4 conform to these crack patterns manifested in the tests. Moreover, this trend indicates that fiber reinforcing has been as effective on brick chip concrete as concrete with stone chips. For comparison with SFRC, both GFRC and SFRC from previous research [20] have been presented in Fig. 17. It is obvious that the behavior pattern is quite similar with some differences. For example, SFRC samples showed strain hardening after macro-crack but GFRC samples did not exhibit this phenomenon. The reason is that SFRC for Fig. 17

Table 4
Summary of flexural tests on test beams with brick chips.

Concrete	Sample ID	Average Micro-crack load, kN	Average Macro-crack load, kN	Macro-crack Toughness, N.m	Average Toughness, N. m	Ultimate Load, kN	Average Ultimate Load, kN	Predicted Ultimate Load, kN	Failure mode
Control	1	23.8	57.4	305	260	61	60	49.13	Shear/ flexural
	2			250		59			Shear/ flexural
	3			270		60			Shear/ flexural
1% GFRC	1	33.2	66.2	245	283	70	70	50.25	Shear/ flexural
	2			320		70			Shear/ flexural
	3			282		71			Shear/ flexural
1.5% GFRC	1	44	65	321	327.9	72	71.4	50.69	Shear/ flexural
	2			232		69			Shear/ flexural
	3			334		73			Shear/ flexural
2% GFRC	1	Not discernible	68.6	372	324	76	73.8	51.3	Flexural
	2			320		70			Flexural
	3			279		75			Flexural
2.5% GFRC	1	Not discernible	69.2	283	303.3	77	76.6	51.69	Flexural
	2			376		81			Flexural
	3			251		72			Flexural
3.0% GFRC	1	Not discernible	68.0	308	289.0	70	72.3	52.13	Flexural
	2			270		75			Flexural
3.5% GFRC	1	Not discernible	68.2	283	286.0	69	68.7	54.14	Flexural
	2			289		68			Flexural

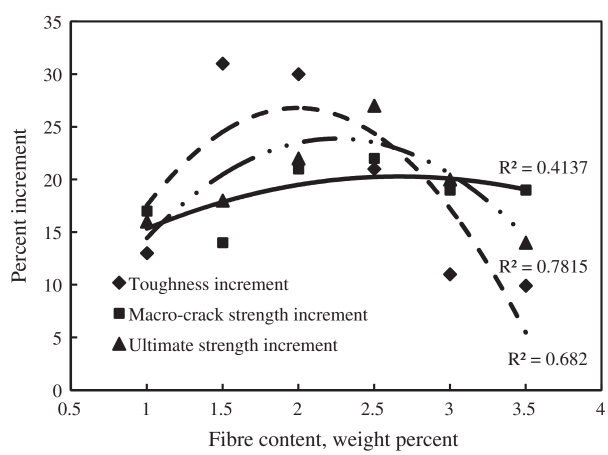

Fig. 13. Various parameter increment trends (for GFRC with BC).

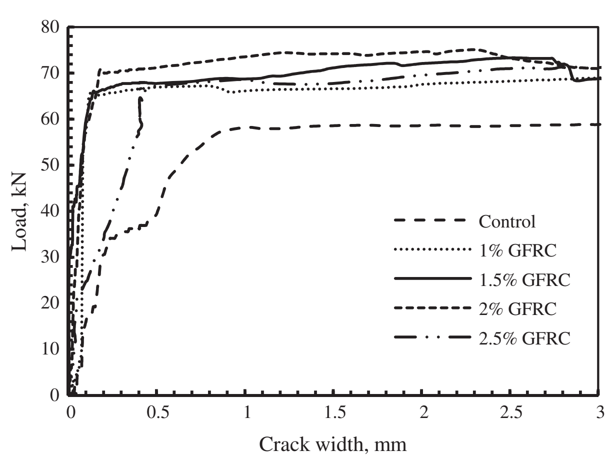

Fig. 14. Load vs. crack width (for GFRC with BC).

was made with high strength steel (steel fiber having yield strength of 1303 MPa and ultimate strength of 1784 MPa) whereas GFRC in current research was made with mild steel (having yield strength of 524 MPa and ultimate strength of 592 MPa). Moreover, GI wire bends easily but steel fiber requires more energy to bend. As a result, GFRC does not show significant strain hardening properties. Nonetheless, GI fiber appears to be an effective means of increasing performance of concrete.

4.1. Cost comparison

Cost analysis of materials for GFRC and SFRC with the mix design chosen in this study shows that GI wire fiber, if used as a substitute of steel fiber, can save BDT 1380 ($17.2) per cubic meter of concrete when fiber dosage is 1% on weight basis, which means a cost reduction of almost 14% [16]. With higher dosage of fiber, reduction in cost increases proportionately.

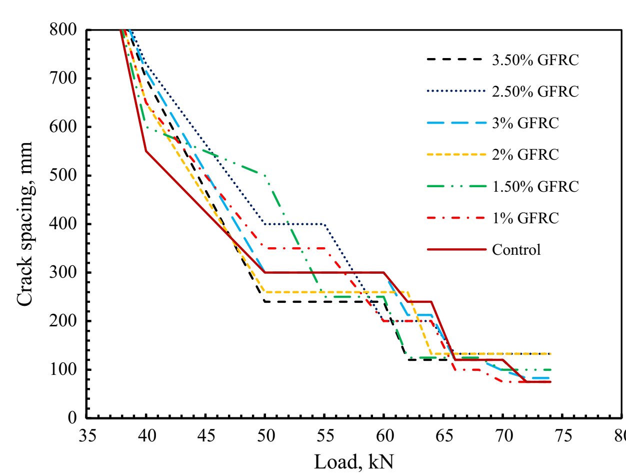

Fig. 15. Average crack spacing vs. Load (for GFRC with BC).

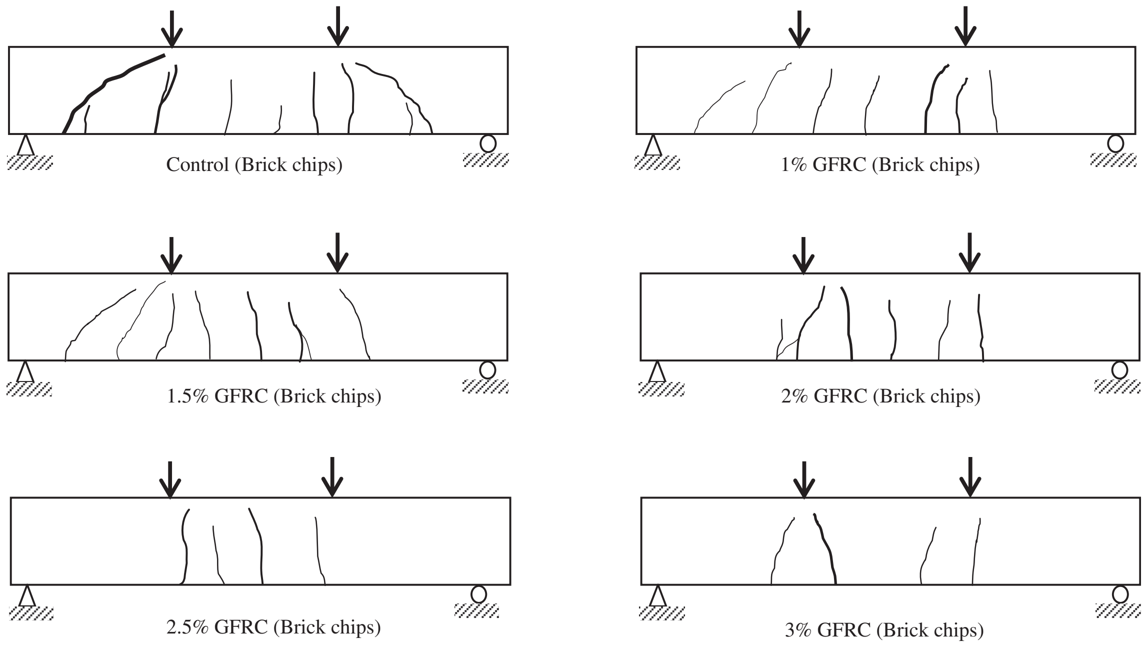

Fig. 16. Crack patterns at ultimate loads for various test specimens.

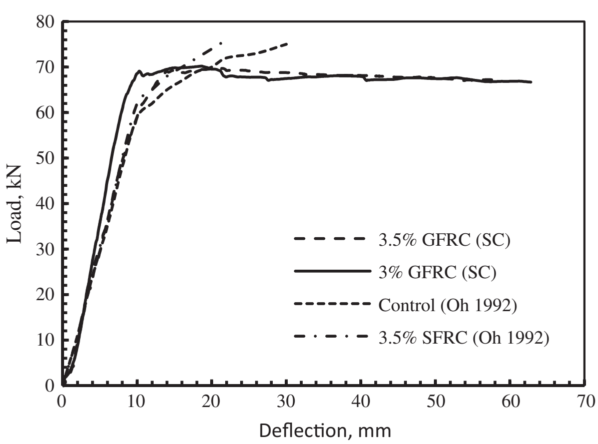

Fig. 17. Load–deflection curves for GFRC and SFRC (SC).

5. Conclusions

Steel fiber reinforcing technique was applied to LWAC with brick chips and locally available GI wire was used as low cost alternative for steel fiber. Fiber content was limited to low volume fraction considering both cost and ease of mixing process. Compressive strength, splitting tensile strength and flexural capacity were investigated. The following conclusions can be made based on the findings from this study:

1. GI wire fiber as concrete reinforcement can be used as a viable low-cost alternative to steel fibers in developing countries like Bangladesh. It can provide significant compressive strength, tensile strength and flexural enhancements to concrete with brick chip aggregates.
2. Result of compressive strength test indicates that concrete compressive strength can be increased by about thirty percent with the addition of GI wire fibers. On the other hand, splitting tensile strength test results show a much higher enhancement, of the order of around forty-five percent due to GI wire fibers incorporation. However, this strength increment is dependent on fiber orientation in the concrete matrix.
3. Various flexural properties of concrete can be enhanced in the range of 15–30% with the addition of GI wire fibers, as observed from the test results. These properties include the first-crack load, flexural toughness and ultimate load.
4. Crack widths in concrete can be remarkably reduced due to GI fiber addition. For the same load, crack widths of the GFRC samples were found to be significantly smaller than that of normal concrete. Crack spacing is also observed to be larger in GFRC during the initial cracking stages, which indicates that fibers delay the formation of cracks as well as resist crack propagation.
5. Crack patterns show significant reduction in crack formation and propagation due to fiber addition to concrete matrices. Addition of GI fiber arrested shear-flexure from forming which validated that fiber reinforcement improves shear resistance in concrete.
6. GFRC produces similar load–deflection behavior as SFRC when stone chips is used as coarse aggregate. Comparison of brick aggregate concrete with other LWAC also shows that fiber addition brings about comparable enhancement, if not more, in mechanical properties i.e. compressive and tensile strength, toughness etc.

In fine, considering overall performance, fiber content of 2–2.5% (approx. 0.6–0.75% vol. fractions) by weight should be suitable for use in conventional concrete mixes with burnt clay brick chips as coarse aggregate. No additional admixture or special attention is necessary for this concrete mix but this fiber addition may impart significant performance enhancement which will, in the long run, ensure a durable structure. Increased wire volume may lead to decreased workability and difficulty in concrete placement, especially for large concrete members. In such cases, utilization of admixture may become necessary.

Disclosure statement

Authors hereby declare that they do not have any competing financial, professional, or personal interests from other parties with regard to any content of this article.

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References

[1] M. Hassanpour, P. Shafigh, H.B. Mahmud, Lightweight aggregate concrete fiber reinforcement–A review, Constr. Build. Mater. 37 (2012) 452–461, http://dx.doi.org/10.1016/j.conbuildmat.2012.07.071.
[2] A.M. Neville, J.J. Brooks, Concrete technology, Pearson Education (Malaysia) Pte. Ltd., PP(CTP), 2008.
[3] V.C. Li, Large volume high performance applications of fibers in civil engineering, J. Appl. Polym. Sci. 83 (3) (2002) 660–686, http://dx.doi.org/10.1002/app.2263.
[4] P.K. Mehta, P.J.M. Monteiro, Concrete; Microstructure, Properties, and Materials, 3rd ed., McGraw-Hill, New York, N. Y, 2006.
[5] J.M. Makar, G.W. Chan, Growth of cement hydration products on single walled carbon nanotubes, J. Am. Ceram. Soc. 92 (6) (2009) 1303–1310, http://dx.doi.org/10.1111/j.1551-2916.2009.03055.x.
[6] T. Manzur, N. Yazdani, Strength enhancement of cement mortar with carbon nanotubes: early results and potential, J. Transp. Res. Board 2142 (2010) 102–108, http://dx.doi.org/10.3141/2142-15.
[7] T. Manzur, N. Yazdani, Optimum mix ratio for nanotubes in cement mortar, KSCE J. Civil Eng. 19 (5) (2015) 1405–1412, http://dx.doi.org/10.1007/s12205-014-0721-x.
[8] P. Ramadoss, K. Nagamani, Tensile strength and durability characteristics of high performance fiber-reinforced concrete, Arabian J. Sci. Eng. 33 (2B) (2008) 307–319.
[9] N.V. Chanh, Steel fiber reinforced concrete, in: Proc., JSCE-VIFCEA Joint Seminar on Concrete Engineering, pp. 108–116, 8–9 December 2005, Ho Chi Minh City University of Technology, Vietnam, 2005.
[10] J. Edgington, D.J. Hannant, R.I.T. Williams, Steel fiber reinforced concrete, Building Research Establishment current paper, CP 69/74, 1974, pp. 154–170.
[11] L. Dvorkin, O. Dvorkin, Basics of concrete science. <http://www.scribd.com/doc/6004561/Basics-of-Concrete-Science>.
[12] G.L. Guerrini, L. Cassar, Biolzi, G. Rosati, Production and mechanical characterization of very high performance fiber reinforced concrete beams, in: Proc. International conference: Innovation in concrete structures: design and construction, University of Dundee, Scotland, UK, Pub. Thomas Telford, 1999, pp. 559–568.
[13] G.F. Peng, W.W. Yang, J. Zhao, Y.F. Liu, S.H. Bian, L.H. Zhao, Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures, Cem. Concr. Res. 36 (4) (2006) 723–727, http://dx.doi.org/10.1016/j.cemconres.2005.12.014.
[14] N.A. Libre, M. Shekarchi, M. Mahoutian, P. Soroushian, Mechanical properties of hybrid fiber reinforced lightweight aggregate concrete made with natural pumice, Constr. Build. Mater. 25 (2011) 2458–2464.
[15] R.V. Balendran, F.P. Zhou, A. Nadeem, A.Y.T. Leung, Influence of steel fibers on strength and ductility of normal and lightweight high strength concrete, Build. Environ. 37 (12) (2002) 1361–1367, http://dx.doi.org/10.1016/S0360-1323(01)00109-3.
[16] M.A.B. Emon, Study of strength and ductility of Galvanized Iron wire reinforced concrete, (M.Sc. thesis), Department of Civil Engineering, Bangladesh University of Engineering & Technology, 2014.
[17] ACI 544.1R:1996, State-of-the-art report on fiber reinforced concrete, American Concrete Institute, Farmington Hills, MI, USA.
[18] F. Bencardino, L. Rizzuti, G. Spadea, R.N. Swamy, Stress-strain behavior of steel fiber-reinforced concrete in compression, J. Mater. Civil Eng. 20 (3) (2008) 255–263, http://dx.doi.org/10.1061/(ASCE)0899-1561(2008) 20:3(255).
[19] M. Musmar, Tensile strength of steel fiber reinforced concrete, Contemp. Eng. Sci. 6 (5) (2013) 225–237, http://dx.doi.org/10.12988/ces.2013.3531.
[20] B.H. Oh, Flexural analysis of reinforced concrete beams containing steel fibers, J. Struct. Eng. ASCE 118 (10) (1992) 2821–2835, http://dx.doi.org/10.1061/(ASCE)0733-9445(1992) 118:10(2821).
[21] D. Otter, A.E. Naaman, Properties of steel fiber reinforced concrete under cyclic loading, ACI Mater. J. 85 (4) (1988) 254–261, http://dx.doi.org/10.14359/2116.
[22] Y. Ou, M. Tsai, K. Liu, K. Chang, Compressive behavior of steel-fiber-reinforced concrete with a high reinforcing index, J. Mater. Civil Eng. 24 (2) (2012) 207–215, http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000372.
[23] ACI 318:2014, Building code requirements for structural concrete, American Concrete Institute, Farmington Hills, MI, USA.
[24] C.D. Johnston, Steel fiber reinforced mortar and concrete, a review of mechanical properties in fiber reinforced concrete, ACI-SP-Detroit (1982), http://dx.doi.org/10.14359/17890.
[25] A.E. Naaman, Engineered steel fibers with optimal properties for reinforcement of cement composites, J. Adv. Concr. Technol. 1 (3) (2003) 241–252.
[26] B. Chen, J. Liu, Contribution of hybrid fibers on the properties of the high strength lightweight concrete having good workability, Cem. Concr. Res. 35 (5) (2005) 913–917, http://dx.doi.org/10.1016/j.cemconres.2004.07.035.
[27] F.A. Mirza, P. Soroushian, Effects of alkali-resistant glass fiber reinforcement on crack and temperature resistance of lightweight concrete, Cem. Concr. Compos. 24 (2) (2002) 223–227, http://dx.doi.org/10.1016/S0958-9465(01)00038-5.
[28] N. Banthia, R. Gupta, Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete, Cem. Concr. Res. 36 (7) (2006) 1263–1267, http://dx.doi.org/10.1016/j.cemconres.2006.01.010.
[29] N. Banthia, Durability enhancements in concrete with fiber reinforcement, in: Proc. International conference: Sustainable construction materials and technologies, Pub. UW Milwaukee CBU, 2007, pp. 209–219.
[30] R. Craig, Flexural behavior and design of reinforced fiber concrete members, ACI SP105 (1987) 517–563, http://dx.doi.org/10.14359/3069.
[31] C.H. Henager, T.J. Doherty, Analysis of reinforced fibrous concrete beams, J. Struct. Eng. ASCE 102 (1) (1976) 178–188, http://dx.doi.org/10.1061/(ASCE)0733-9445(1992) 118:10(2821).
[32] R.N. Swamy, S.A. Al-Ta'an, Deformation and ultimate strength in flexure of reinforced concrete beams made with steel fiber concrete, ACI Mater. J. 78 (5) (1981) 395–405, http://dx.doi.org/10.14359/10525.
[33] S. Haroon, N. Yazdani, K. Tawfiq, Post-tensioned anchorage zone enhancement with fiber reinforced concrete, ASCE J. Bridge Eng. 11 (5) (2006) 566–572, http://dx.doi.org/10.1061/(ASCE)1084-0702(2006) 11:5(566).
[34] P. Shafigh, H.B. Mahmud, M.Z. Jumaat, Effect of steel fiber on the mechanical properties of oil palm shell lightweight concrete, Mater. Design 32 (7) (2011) 3926–3932.
[35] O.A. Duzgun, R. Gul, A.C. Aydin, Effect of steel fibers on the mechanical properties of natural lightweight aggregate concrete, Mater. Lett. 59 (27) (2005) 3357–3363, http://dx.doi.org/10.1016/j.matlet.2005.05.071.
[36] G. Campione, C. Cucchiara, L.L. Mendola, M. Papia, Steel–concrete bond in lightweight fiber reinforced concrete under monotonic and cyclic actions, Eng. Struct. 27 (6) (2005) 881–890, http://dx.doi.org/10.1016/j.engstruct.2005.01.010.
[37] ACI 544.3R:2008, Guide for specifying, proportioning, mixing, placing, and finishing steel fiber reinforced concrete, American Concrete Institute, Farmington Hills, MI, USA.
[38] ASTM A820/A820M:2011, Standard specification for steel fibers for fiber-reinforced concrete, ASTM International, West Conshohocken, PA, USA.
[39] I.B. Topcu, M. Canbaz, Effect of different fibers on the mechanical properties of concrete containing fly ash, Constr. Build. Mater. 21 (7) (2007) 1486–1491, http://dx.doi.org/10.1016/j.conbuildmat.2006.06.026.
[40] C.T. Tsai, L.S. Li, C.C. Chang, C.L. Hwang, Durability design consideration and application of steel fiber reinforced concrete in Taiwan, Arabian J. Sci. Eng. 34 (1B) (2009) 57–79.
[41] ASTM C39/C39M:2014, Standard test method for compressive strength of cylindrical concrete specimens, ASTM International, West Conshohocken, PA, USA.
[42] G. Campione, N. Miraglia, M. Papia, Mechanical properties of steel fiber reinforced lightweight concrete with pumice stone or expanded clay aggregates, Mater. Struct. 34 (4) (2001) 201–210, http://dx.doi.org/10.1007/BF02480589.
[43] J. Gao, W. Suqa, K. Morino, Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete, Cem. Concr. Compos. 19 (4) (1997) 307–313, http://dx.doi.org/10.1016/S0958-9465(97)00023-1.
[44] T.H.K. Kang, W. Kim, Y.K. Kwak, S.G. Hong, Shear testing of steel fiber-reinforced lightweight concrete beams without web reinforcement, ACI Struct. J. 108 (5) (2011) 553–561, http://dx.doi.org/10.14359/51683212.
[45] ASTM C496/C496M: 2011, Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM International, West Conshohocken, PA, USA.
[46] O. Kayali, M.N. Haque, B. Zhu, Some characteristics of high strength fiber reinforced lightweight aggregate concrete, Cem. Concr. Compos. 25 (2) (2003) 207–213, http://dx.doi.org/10.1016/S0958-9465(02)00016-1.
[47] M.I.M. Rjoub, Moment capacity of steel fiber reinforced concrete beams, J. Eng. Sci. 34 (2) (2005) 413–422.
[48] W.A.H. Abu Hijab, Flexural strength of lightweight and normal concrete beams with steel fibers (M.Sc. Thesis), University of Jordan, Jordan, 1999.
[49] S. Ashour, K. Mahmoud, F. Wafa, Influence of steel fiber and compression reinforcement on deflection of high strength concrete beams, ACI Struct. J. (1997) 611–624.