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Research paper

Experimental investigation of chopped steel wool fiber at various ratio reinforced cementitious composite panels

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Abstract: The flexural toughness of chopped steel wool fiber reinforced cementitious composite panels was investigated. Reinforced cementitious composite panels were produced by mixing of chopped steel wool fiber with a ratio range between 0.5% to 6.0% and 0.5% as a step increment of the total mixture weight, where the cement to sand ratio was 1:1.5 with water to cement ratio of 0.45. The generated reinforced cementitious panels were tested at 28 days in terms of load-carrying capacity, deflection capacities, post-yielding effects, and flexural toughness. The inclusion of chopped steel wool fiber until 4.5% resulted in gradually increasing load-carrying capacity and deflection capacities while, provides various ductility, which would simultaneously the varying of deflection capability in the post-yielding stage. Meanwhile, additional fiber beyond 4.5% resulted in decreased maximum load-carrying capacity and increase stiffness at the expense of ductility. Lastly, the inclusion of curves gradually.

Keywords: Steel fibers, Chopped steel wool fiber, Cementitious composites panels, Load carrying capacity

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1. Introduction

The improvement of the quality and performance of concrete materials has attracted the attention of the research community working in this field. structural sophistication, increase in structural height for accommodation and rapid increase in population have necessitated the quest of high load-bearing materials [1–2]. However, the air pollution caused by steel bar production in the form of nitrous oxide and carbon dioxide/monoxide resulted in the attempt to find possible alternatives or to reduce the usage for the depletion of a steel bar of the concrete which will consequently decrease the rate of global warming in terms of construction materials production [3–4]. the steel fibers (SF) are suitable to be reinforced, making it a popular material that is being used for many applications and processes such as refractory linings, blast resistance structure, tunnel linings, pavements, and precast concrete unit [5–7].

Beams are traditional descriptions of buildings or civil engineering structural elements. However, any structural systems containing beam structures that are designed to carry lateral loads are analyzed in a similar method. Most of the existing beams, thin shells, and panels in composites structures require high resistance to maintain their performance. Based on the review of the literature, it was found that some researches had been conducted on the application of SF in the cementitious composite. Some of the researchers noted that steel fiber was effective in contributing to flexural toughness optimization only when the steel fiber content is less than 2% [8]. Meanwhile, the inclusion of steel fibers showed significant improvement to the flexural strength and toughness of samples with content less than 3% [9]. Besides, they also mentioned that the post-crack load dropped at the higher fiber content of fiber reinforced concrete. Furthermore, the addition of SF content from 0.5% to 1.5% resulted in a gradual increase in the maximum load and the energy absorption [10].

Chopped steel wool fiber (CSWF) is considered a techno-economic material, which can be produced from recycled metal scrap [11]. However, reinforcement of cementitious composite panels by CSWF is still questionable due to the lack of collected data related to the correlations between the generated reinforced cementitious matrices and the CSWF inclusions which remains unclear particularly in terms of load-carrying capacity, deflection capacities, post-yielding effects, and the flexural toughness. Therefore, the main goal of this study is to investigate CSWF at various ratios of reinforced cementitious composite panels.

2. Materials and methods

For the reinforcement in the cement matrix, chopped Steel wool fibers produced from recycled metal scrap which are obtained from Rahamatullah Sdn Bhd (Kedah, Malaysia) have been used as reinforcement materials. The specifications of SWFC used were listed as following; young's modulus of 210 MPa, length & diameter of 4 mm (max) & 25 µm (max) respectively, the tensile strength of steel fiber varying from 966–1242 MPa, and specific gravity of 7.8g/cm3.

The Ordinary Portland Cement (OPC) which was known as Lion Blue, manufactured in Malaysia was used. The cement used complies with BSEN196 and MS522 where its chemical compositions were in the standard range of 70%, 17%, 3.9%, 3.60%, 3.2%, and 1.50% for CaO, SiO_2, Al_2O_3, SO_3, Fe_2O_3, and MgO, respectively. The cement was locally available and obtained from Perlis factory was used as fine aggregate, which has been washed, dried and size sieved with diameters range of (1.18 mm $\leq$ Sand size $<$ 200 µm) as recommended in the previous work [12]. The preparation of reinforced cementitious composite panels was done by mixing steel fibers ratio ranged between 0.5 to 6.0 with 0.5 as step increment of the total mixture weight, where the cement to sand ratio was 1:1.5, and water to cement ratio 0.45. The mold size of 25×100×500 mm was used. Thirty-six (36) samples have been prepared and the mean values of the three for each batch were obtained and the test was conducted at 28-days.

Correlation coefficients were used to describe the quality of the relationship between CSWF inclusion and load carrying capacity, deflection capacities, post-yielding effects, and flexural toughness as variables that are related to each other.

Flexural toughness was examined according to the method for determining the toughness of FRC proposed by the Japan Concrete Institute. The method, JSCE–G 552 is a testing method for examining the bending strength and bending toughness of fiber reinforced concrete using a simple beam by three-point bending. Through this technique, the area under the load-deflection plot up to a deflection span/150 was obtained. This measure can be considered as energy absorption capacity.

3. Results and discussions

3.1. load carrying capacity

During the application of load, the continuous appearance of cracks was observed on the beams. The load at the first crack of all the beams was noted and then plotted at this stage. Furthermore, the stage at which the specimen does not have enough capacity to carry further load is known as an ultimate loading capacity. At this stage, deflections may increase but the load-carrying capacity is reduced. The load-carrying capacity for each type of beam was noted and presented in Fig. 1.

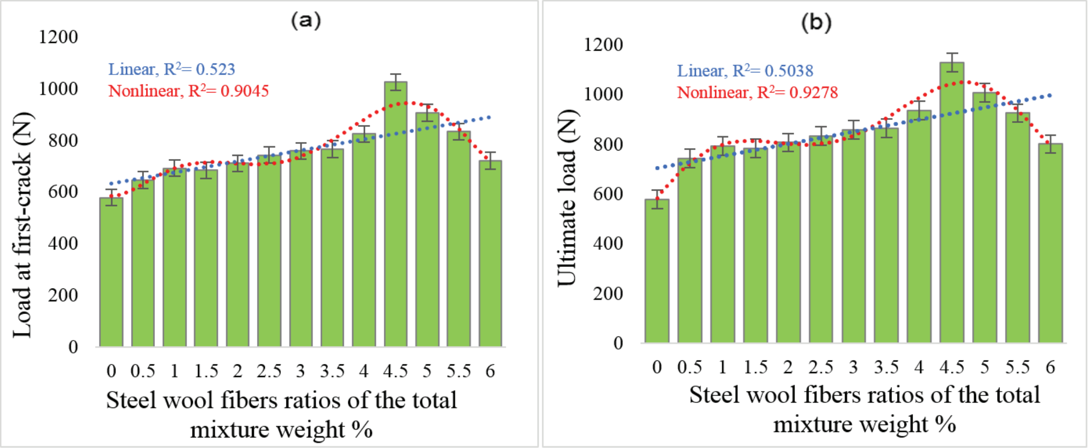


Fig. 1. Load-carrying capacity with different addition ratios of chopped steel wool fiber: (a) load at first-crack and (b) ultimate load

In general, beams with chopped steel wool fiber exhibited better behavior than those without fiber. There was an improvement in the values compared to the conventional cement mortar. It can be clearly said that, when the CSWF ratio was changed from 0.5% to 6.0%, the highest load-carrying capacity for cement mortar was achieved at a ratio of 4.5%. Initially, the increase in the CSWF concentration improved the load-carrying capacity where the maximum increase rate was 77.2% and 95.3% for the load at the first crack and ultimate load respectively. However, an inverse relationship was observed in the case of the CSWF concentration of more than 4.5%. There was a reduction of the values, calculated from the maximum load-carrying capacity where the maximum decrease rate was 29.6% and 29.1% respectively at 6% steel wool fibers.

The relationships between load-carrying capacity and different addition ratios of chopped steel wool fibers can be estimated according to the higher correlation coefficients R^2, as presented in Fig. 1 which was a nonlinear relationship using a 6-degree polynomial equation. There is an unclear linear correlation between the generated reinforced cementitious matrix and the inclusions of CSWF.

This improvement could be due to fiber distribution behavior which became more uniformed. Furthermore, the performance of fiber depends on its orientation in the composite matrices where the optimum mechanical properties are in the direction of the reinforcement. Fiber orientation in the cementitious composite is a dependent function of the fiber properties, matrix properties, the casting process, and the change in shape produced by the processing. Meanwhile, the orientation of fibers in the cementitious composite structure members has a significant effect on the mechanical properties because the fibers support much of the strength, stiffness properties, and elongation along with their axis directions.

Furthermore, the influence of fiber orientation in cementitious composite depends on the loading conditions e.g., beams, slabs, columns, and walls which are subjected to deformation (i.e., compression, tension, and flexural) as a function of the applied load. Generally, as clearly seen in Fig. 2, the efficiency of fiber orientation can be interpreted through a schematic diagram by testing a supported beam under three-point loading that presents fibers in three different directions which are: (a) fibers are not on the load direction/perpendicular on the load direction, (b) fibers depend on the orientation angle and (c) fibers on the load direction.

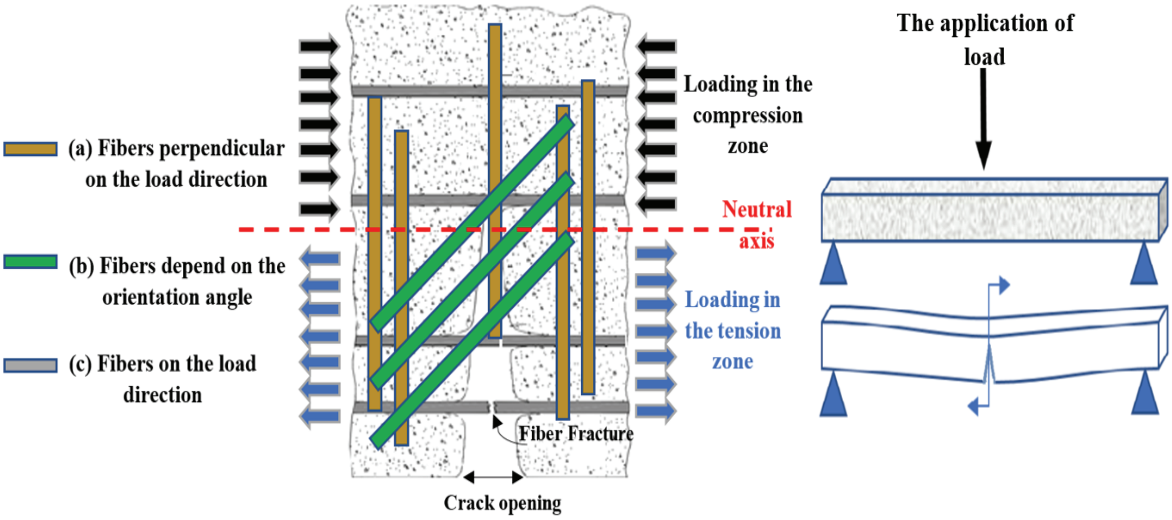
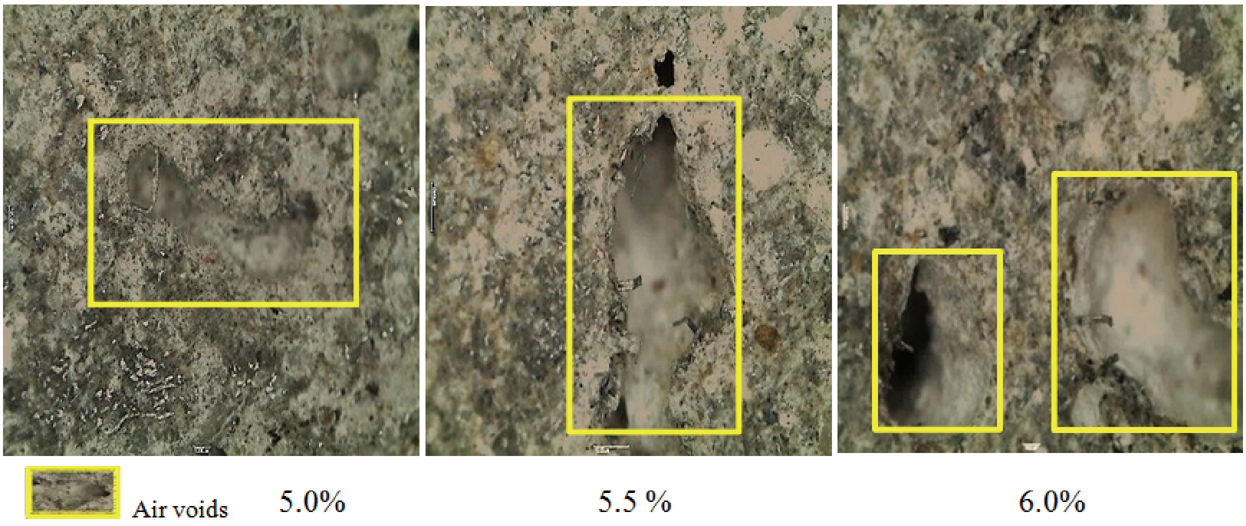


Fig. 2. Schematic diagram to describe the fiber orientation efficiency

Proper distribution of CSWF in cementitious composites is crucial to optimize the effectiveness of fibers in improving the physical and mechanical properties especially in terms of fibers orientation and location within the sample. Hence, it has always been a challenge to produce well-distributed fibers that are used as reinforcements in the concrete matrix. A non-uniform fiber distribution contributes to the underutilization of steel wool fibers and causes lower performance of mortar samples. Therefore, the optimum fiber orientation should be in the same load direction.

Otherwise, the decline of the values is due to the air voids. Usually, composite materials consist of two separate components, the matrix and the reinforcing materials [13]. The cementitious matrix provides a quality and an acceptable compressive strength which are the components that hold the reinforcement together in place to form the bulk of the material, while the reinforcement is incorporated in the matrix to increase its resistance, especially its tensile strength. Thus, the performance of the cementitious composite material is a shared responsibility between the matrix and fibers.

The effects of air voids on the strength can be explained by the air voids in hardened concrete which are mostly in the form of large voids and pockets. Therefore, the pressure resistance (the load application) that the matrix can tolerate will decrease due to the removal of voids. Meanwhile, without fiber reinforcement, higher tendency to leave free spots without fiber reinforcing. It can be distinctly said that the increase in fiber fraction beyond 4.5% will increase and also change the air void distribution of a mixture, consequently decreasing the load-carrying capacity as a strength function, which can be seen in Fig. 3. This finding is aligned with previous studies where it was noted that an excessive amount of steel fiber added can change air voids distribution [14–17]. Besides, the imbalance of fibers reinforcement where certain areas are covered by fibers that are closely localized leads to the ability to withstand higher strength compared to certain areas with the non-existence of fibers. Hence, the cementitious samples will fail at the weak areas where the fibers are not located compared to other areas which CWSF is located to reinforce at the particular area. This also leads to weaker flexural performance.



5.0% 5.5 % 6.0%

Fig. 3. The air voids in samples 5%, 5.5% and 6% due to an excessive amount of fiber

3.2. Deflection capacities

The deflection refers to the displacement of the beam from its original position due to the bending, which is determined from deformation taking place along the span of the beam when loads are being applied. The deflection capacity development of cement mortar samples with different addition ratios of CSWF is shown in Fig. 4. As can be seen, inclusion of the CSWF from 1% to 4.5% has increased the deflection capacities (first crack and midspan deflection) by (4.73%, 8.82%), (7.74%, 14.41%), (8.17%, 17.63%), (15.48%, 17.4%), (22.80%, 35.70%), (46.02%, 57.85%), (61.51%, 75.7%) and (63.44%, 75.84%), at 28 days of curing period, respectively, until it reached a maximum value at 4.5% and thereafter decreased at higher CSWF contents (4.5%). Therefore, according to the higher correlation coefficients R^2 the relationships were nonlinear using 4-degree polynomial equations.

Based on this result, optimizing the load-carrying capacity through the inclusion of CSWF may affect the generated composite stiffness which changes the ductility. The deflection decreased at higher CSWF contents due to the increased stiffness. On the other hand, stiffness is resistant against deflection, which means that higher stiffness will beat the low deflection and cracks will begin to appear sooner even though the generated composite showed acceptable ductility.

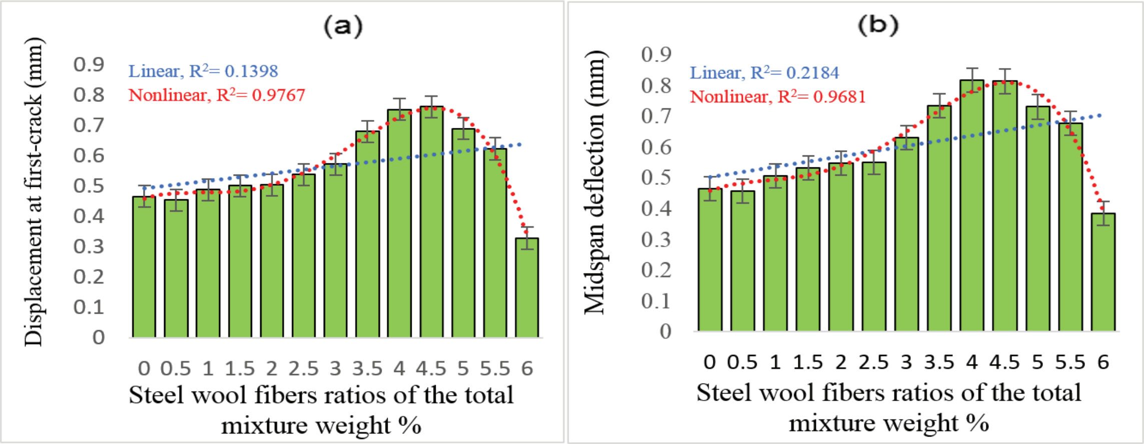


Fig. 4. Deflection capacities with different addition ratios of chopped steel wool fiber: (a) displacement at first crack and (b) midspan deflection

3.3. Post-yielding effects

As shown in Fig. 5, from the post-yield effect, from the first cracking to the final ultimate load and flexural capacity, the micromechanical advantages of adding CSWF to conventional concrete can be seen. It can be clearly observed that the incorporation of steel fibers in concrete imparts ductility to other fragile materials. They make the concrete continue to bear the load after cracking, which is also, called post-cracking behavior. The incorporation of short fibers can lead to an increase in load-bearing capacity and ductility in the post-cracking stage.

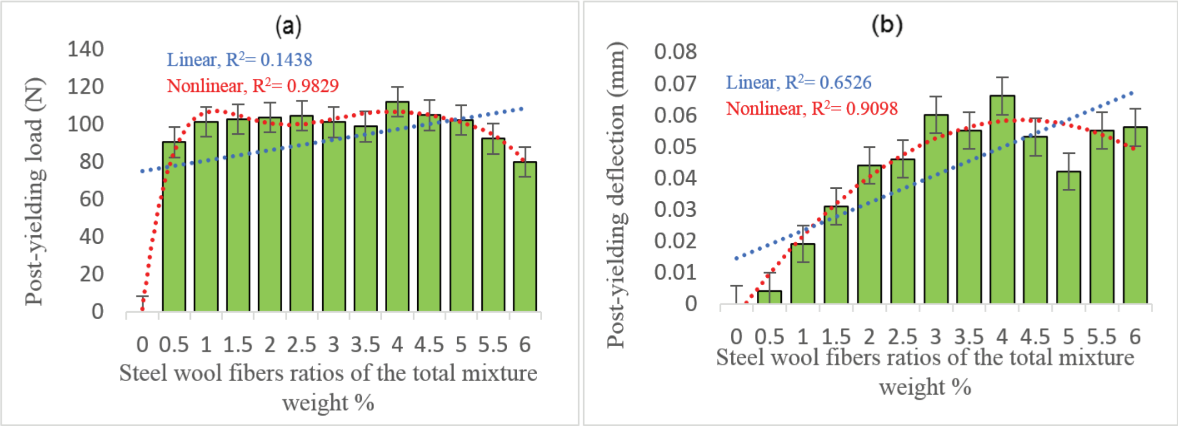


Fig. 5. Post-yielding effects with different addition ratios of chopped steel wool fiber: (a) post- yielding load-carrying capacity and (b) post-yielding deflection capacity

This increase can be due to the crack arresting mechanism of the closely spaced fibers [18–19]. Furthermore, the main role of the fibers is to bridge across the matrix cracks that are developed as concrete is loaded, and thus providing some post-cracking ductility. The non-uniformly distributed CSWF holds the cracks that developed initially and progressively under the application of loads. This provides a variety of ductility, which will increase the deflection ability at the same time depending on the fiber distribution.

3.4. Flexural toughness

Flexural toughness is defined as a measure of the energy absorption capacity, or in other words, the ability to withstand crack opening. It is the performance of area under the load-deflection curve or area under stress-strain achieved by testing a simply supported beam under three-point loading.

The energy absorption capacities development of cement mortar samples with different addition ratios of CSWF are shown in Fig. 6. As can be seen, the CSWF concentration has a significant effect on the energy absorption capacities. Increasing the steel wool fibers has increased the energy absorption. It can be observed that, when the CSWF ratio was changed from 0.5% to 6.0%, the highest energy absorption capacity about cement mortar was achieved at a ratio of 4.5%. Initially, the increase of the CSWF concentration improved the energy absorption rapidly. At the fiber content of 0.5% to 4.5% the maximum increase rate was 185.97% at a fiber ratio of 4.5% even though there was a slight reduction of the increase in rate values, which were 155.06%, 175.59%, and 183.58% at 5.0%, 5.5%, and 6.0% CSWF respectively, due to the size of the void distribution which is caused by the excessive amount of fibers. Meanwhile, based on the results of the experiments, the empirical formulae proposed showed the contribution of the incorporation of

CSWF to the energy absorption capacity as illustrated in Fig. 6, where y is the apparent energy absorption capacity (N·mm) and x is CSWF ratios of the total mixture weight.

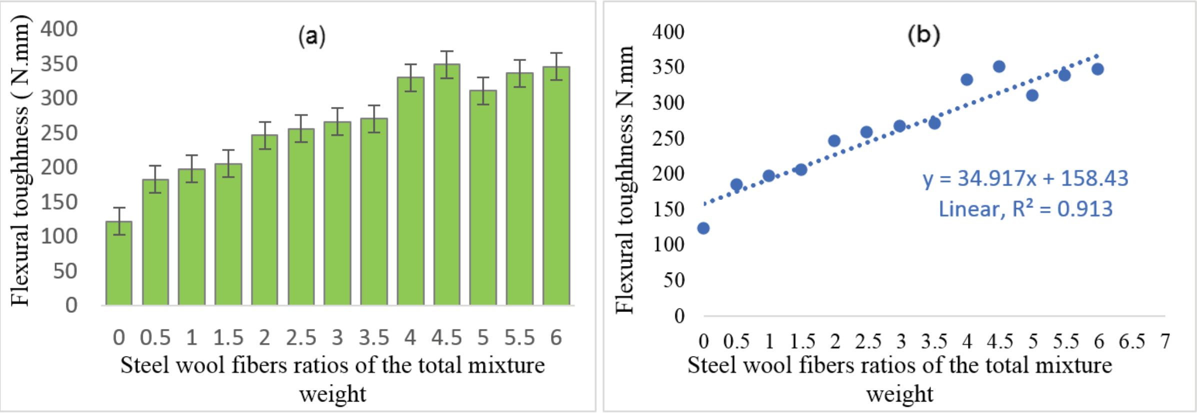


Fig. 6. Flexural toughness with different addition ratios of chopped steel wool fiber: (a) flexural toughness values of composite matrix corresponding to the steel wool fibers ratios, (b) correlation between flexural toughness and steel wool fibers addition

Based on the results, the equation suggests the existence of a significant linear correlation between CSWF addition and the energy absorption capacity. It can be distinctly said that the higher correlations (R^2) were observed, thus suggesting that the equation could be employed. Nevertheless, an excessive amount of added steel fiber leads to a reduction of the workability and segregation of the mixture. Other than that, the closely spaced fibers improved the toughness of concrete and helped to control cracking, where bridging leads to the redistribution of stresses, which imposes a new state of equilibrium across the cross-section after cracking leads to more energy absorption [20]. Fig. 7 illustrates that there is no significant correlation between deflection and load capacities where the flexural toughness depends on the area under the load-deflection plot up to a deflection span/150. The degree of the deflection and load action which are presented as behavior has a great effect on energy absorption capacities.

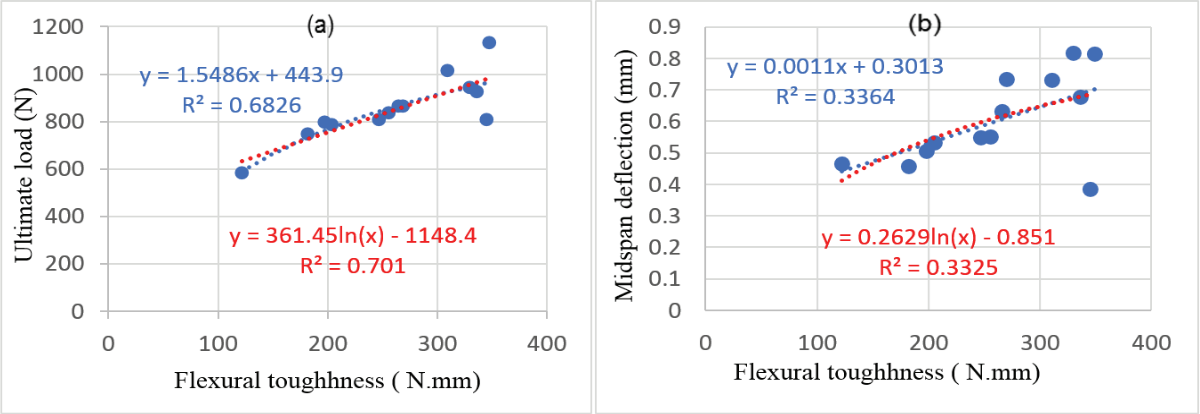


Fig. 7. Flexural toughness correlations corresponding to: (a) ultimate load, (b) deflection

Fig. 8 presents the testing results for a single batch of the generated cementitious composite panels represented by a load-deflection curve with 0.5 offset in the x-axis by different addition ratios of CWSF. As can be seen, the inclusion of the CSWF has improved the behavior of the area under the load-deflection curves. Flexural toughness depends on the load and deflection capacities as a behavior. Three kinds of behaviors can be seen: deflection drop sharply, softening, and semi-hardening. It can be clearly said that the incorporation of steel fibers contents in concrete caused a gradual increase in the area under the load-deflection curve, consequently resulting in increased flexural toughness.

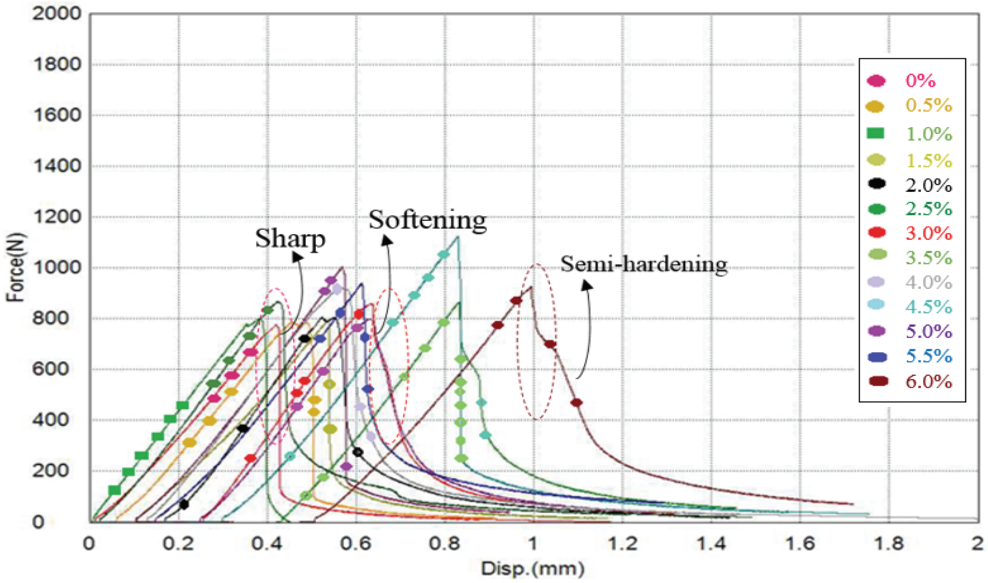


Fig. 8. Single batch of the load - deflection curve by different addition ratios

4. Conclusions

The efficiency of chopped steel wool fiber reinforced cementitious composite panels can be estimated by the generated load capacities, stiffness, ductility, and energy absorption capacities development. Based on the experimental findings, the correlation between the generated load capacities and the chopped steel wool fiber content was nonlinear, with the optimum ratio of fiber content discovered at 4.5% which resulted in a maximum increase rate of 77.2% and 95.3% for the load at the first crack and ultimate load respectively, meanwhile, increasing the deflection capacities (first crack and mid-span deflection) by 63.44% and 75.84% respectively. However, the addition of fiber beyond 4.5% decreased the maximum load-carrying capacity and increased stiffness at the expense of ductility. The objective of this research has been achieved when chopped steel wool fiber improved the behavior and maximized the area under the load-deflection curves gradually.

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