

EFFECT OF FIBER TYPES ON FLEXURAL PERFORMANCE OF COMPACTED CEMENT-FIBER-SAND

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Abstract

This paper presents the effect of 3 different fiber types on the flexural performance of compacted cement-fiber-sand (CCFS) with 4 fiber fractions (0.5, 1.0, 1.5, and 2.0% by volume). The types of fibers are short steel, long steel, and polypropylene fibers. The overall CCFS performance was divided into 5 sub-design performance indicators: (1) peak strength, (2) peak-to-first peak strength ratio, (3) residual strength ratio, (4) toughness, and (5) equivalent flexural strength ratio. Finally, the effectiveness of each fiber type was compared and rated in terms of the overall performance. The results show that the long steel fiber provided the best overall sub-performance, resulting in excellent overall flexural performance.

Keywords: Composite materials, fiber-reinforced soil, flexural strength, pavement materials

Introduction

Compacted cement-sand (CCS) is extensively utilized worldwide as a pavement base and in subbase applications (Consoli *et al.*, 2011; Jamsawang *et al.*, 2015a) due to its high compressive strength. In reality, the pavement structures are subjected to flexural stresses rather than compressive stresses, whereas CCS

has low flexural strength compared to its compressive strength. Moreover, CCS exhibits brittle behavior under flexural loading (Sukontasukkul and Jamsawang, 2012; Onyejekwe and Ghataora, 2014; Jamsawang *et al.*, 2015a), while ductile behavior is required for pavement materials to prevent immediate

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failure due to excessive traffic load, to save costs in terms of increasing the performance life of the pavement, and to reduce the frequency of maintenance operations (Disfani *et al.*, 2014).

The inclusion of fibers in CCF has led to substantive improvements in flexural performances (Sukontasukkul and Jamsawang, 2012; Onyejekwe and Ghataora, 2014; Jamsawang *et al.*, 2015a; Anggraini *et al.*, 2017) because fibers capture and redistribute loads through their tensile strength, mobilizing a wider mass of CCS and thereby improving the mechanical response of the composite material (Festugato *et al.*, 2017). Jamsawang *et al.* (2015a) presented the effect of the fiber and cement contents on the flexural response of compacted cement-fiber-sand (CCFS) using 1 type of polypropylene fiber, whereas the influence of fiber types on the flexural performance of cement-admixed soft clay was investigated by Sukontasukkul and Jamsawang (2012) using short steel, long steel, and polypropylene fibers.

Previous studies of the flexural response of CCFS addressed the different matrix composition and fiber volume fractions with only 1 fiber type. Moreover, the effect of fiber types on flexural performance has not been comprehensively studied. This study focuses on the sub-flexural performance indicators of peak strength, peak strength ratio, residual strength ratio, toughness, and equivalent flexural strength. Finally, the effect of the fiber type on the overall performance of CCFS was evaluated and rated in this study to determine

a suitable fiber type for use in pavement materials.

Experimental Program

Materials

The sand used in the present experimental tests was obtained from Ayutthaya province, Thailand. It is commonly used as a construction material for embankments, filling, and pavement applications. This sand is classified as poorly graded sand with angular and sub-angular shapes. The cement used in the tests was ordinary Portland cement type I. Figure 1 shows the shape and feather of the 3 fiber types that were used in this study, the short steel, long steel, and polypropylene fibers respectively, and Table 1 shows the mechanical properties of the 3 fiber types.

Specimen Preparation

For the preparation of all the CCS and CCFS specimens, dry sand was mixed in a concrete mixer with Portland cement for 3 min, and then the fibers at specific contents were randomly included and mixed for an additional 3 min. Water was added to the cement-fiber-sand mixture to attain the optimum water content (obtained from the standard Proctor test) and was followed by being mixed thoroughly for 5 min. The specimens were then prepared in the form of a beam with the dimensions of 350 mm length, 100 mm width, and 100 mm depth. The fiber



Figure 1. Different fiber types used in this study

Table 1. Properties of the fibers (from the manufacturer)

Type	Steel	Steel	Polypropylene
Length (mm)	35	60	58
Shape	Hooked	Hooked	Crimped
Section	Circular	Circular	Flat
Diameter or width (mm)	0.55	0.90	0.5
Specific weight	7.8	7.8	0.90
Aspect ratio	64	67	52
Tensile strength (MPa)	1100	1100	450

contents were varied among 0.5, 1.0, 1.5, and 2.0% of the sand volume, whereas the cement content was fixed at 5% by weight of the dry sand. The specimens were demolded after 24 h and wrapped with a plastic sheet for a 28-day curing period prior to the test date. After curing for 28 days, the specimens were subjected to a flexural performance test according to ASTM C1609/C1609M (ASTM, 2012).

Parameters Describing Flexural Behavior of CCFS

The flexural responses of CCFS can generally be classified as either deflection-softening or deflection-hardening (Nematollahi *et al.*, 2014; Jamsawang *et al.*, 2015a), as shown in Figure 2. A CCFS sample showing the deflection-hardening behavior generates a higher load-carrying capacity after the first cracking, in comparison with CCS and deflection-softening CCFS. In this research, the point on the load-deflection curve that

clearly shows nonlinearity is defined as the first cracking point (Kim *et al.*, 2011; Nematollahi *et al.*, 2014; Jamsawang *et al.*, 2015a). The load value at this point is termed P_1 and the corresponding deflection value is δ_1 . The peak load (P_p) is defined as the point at which softening first occurs after point P_1 . Thus, $P_1 = P_p$ is noted in the case of deflection-softening CCFS. In addition to the P_1 and P_p points, a deflection point of $L/150$ corresponding to 2 mm for a 300-mm-span length specimen is recommended according to ASTM Standard C1609/C1609M (ASTM, 2012). The flexural strength (f) at any deflection is obtained from:

$$f = \frac{PL}{bd^2} \quad (1)$$

where L is the span length, b is the width of the specimen, and d is the depth of the specimen. The flexural strengths corresponding to the P_1 and P_p are defined as the first peak strength (f_1) and peak strength (f_p), respectively. The load carried by CCFS after P_1 at the deflection of $L/150$ is termed the residual load P_{150} , which corresponds to the residual strength at a deflection of $L/150$ (f_{150}). The energy equivalent to the area under the load-deflection curve up to a given deflection is defined as the toughness. T_{150} is specified as the toughness value at the deflection of $L/150$.

The flexural performance of CCFS is commonly evaluated using the equivalent flexural strength ratio ($R_{T,150}$), which is determined from the energy absorption capacity up to the deflection of $L/150$ of the beam span and the first peak load. Therefore, from the load-deflection curves obtained from

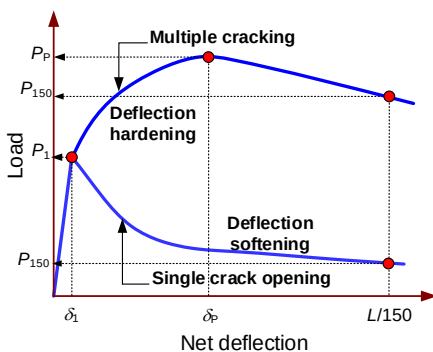


Figure 2. Parameter calculations obtained from load-deflection curves (adapted from ASTM C1609-10 (ASTM, 2010))

the measurements, the value of $R_{T,150}$ can be calculated using the following Equation 2:

$$R_{T,150} = \frac{T_{150}}{P_1 \frac{L}{150}} \times 100\% \quad (2)$$

An $R_{T,150}$ providing a value higher than 100% is associated with $P_p > P_1$ and indicates a high-toughness material. Therefore, $R_{T,150}$ values are smaller and greater than 100% for deflection-softening ($P_p = P_1$) and deflection-hardening ($P_p > P_1$) behaviors, respectively.

Analysis and Discussion on Test Results

Behavior of Load-deflection Curves

Figure 3(a-d) presents the load-deflection curves for the CCS and CCFS beams with different fiber types and fiber contents. For the CCS, the specimen shows deflection-softening

and brittle behavior whereas the CCFS beams show deflection-hardening responses except for the CCFS with 0.5% polypropylene fiber. In contrast, the CCFS beams with short and long steel fibers show a fully developed deflection-hardening response.

First Peak Strength (f_1) and Peak Strength (f_p)

Figures 4(a) and 4(b) show the effect of the fiber type and fiber content on the values of f_1 and f_p , respectively. The f_1 value for the CCS is 0.36 MPa, whereas the values for the CCFSs range from 0.40 to 1.45 MPa. The overall f_p increases according to increasing fiber contents of all the CCFS samples. The CCFSs with long steel fiber provide higher f_p than the CCFSs with short steel fiber and polypropylene fiber; the long steel fiber contributed to the highest values of 0.75 to 1.65 MPa for the 0.5 to 2% fiber content; as a result, the peak strengths of CCS were improved by factors of 2.1 to 4.6.

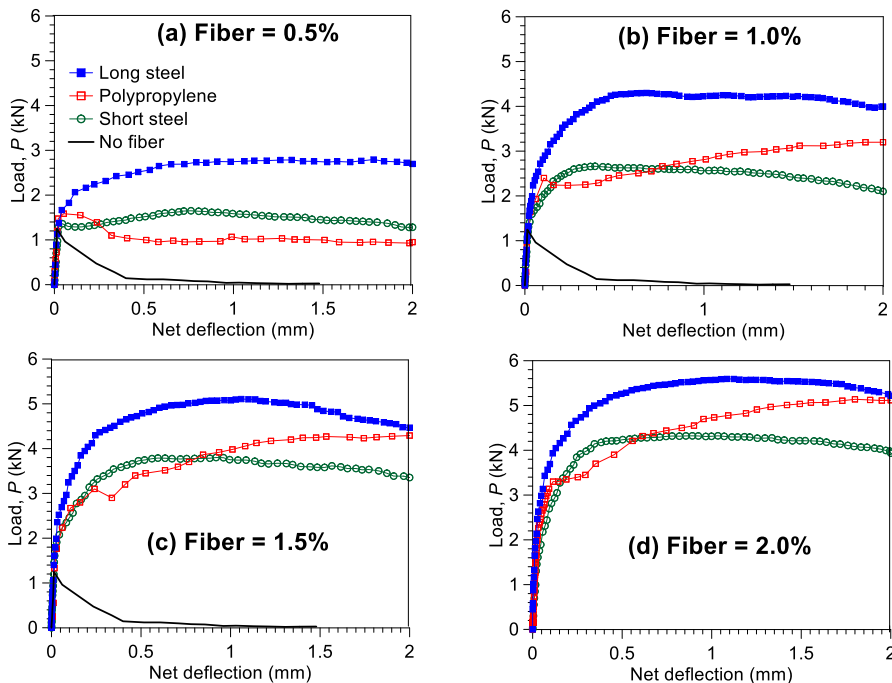


Figure 3. Load-deflection curves for CCS and CCFS with different fiber types and different fiber contents

Peak Strength Ratio

In this study, the comparative degree of hardening of each CCFS is evaluated in terms of a peak strength ratio (PSR), which is defined as f_p divided by f_1 . This ratio indicates the ability of the fiber to gain strength after the first crack has occurred. More specifically, values of $PSR = 1$ and $PSR > 1$ also indicate softening and hardening responses, respectively. Then, the higher PSR value provided the higher degree of hardening. Figure 5 shows that short and long steel fibers provided an increase in PSR with the increasing fiber content and that they give the highest PSRs of 1.4 and 1.8, respectively, at 2% fiber content, whereas polypropylene fiber shows an optimum fiber content of 1% with maximum PSRs of approximately 1.4.

Residual Strength Ratio at a Deflection of L/150

In addition to PSR, a residual strength ratio at a deflection of L/150 (RSR_{150}) is also introduced in this study to measure the ability of each fiber type to carry the residual load from the first crack point to the deflection of L/150. Thus, RSR_{150} can be defined as f_{150} divided by f_1 . This ratio also implies the effectiveness of each fiber type in maintaining the hardening of CCFS at a large deflection, e.g., $RSR_{150} < 1$ and $RSR_{150} > 1$ and also indicates softening and hardening responses at a deflection of L/150, respectively.

The results for the polypropylene fiber (Figure 6) show that the fiber content of 1.0 is the optimum to obtain the maximum RSR_{150} value of approximately 1.4. However, RSR_{150} increased with the increasing fiber contents for short and long steel fibers yielding the highest values for each of 1.3 and 1.75, respectively, at 2% fiber content. It seems that long steel fiber was the most effective in terms of RSR_{150} among the fiber types.

Toughness at a Deflection of L/150

The toughness at a deflection point of 2 mm corresponding to L/150 (T_{150}) was considered in this study. The results show that the T_{150} of CCFS is found to be dependent upon the fiber content and fiber type, as shown

in Figure 7. Higher fiber contents exhibited a greater T_{150} for all fiber types, owing to the improvement of the fiber bridging capacity at the crack surfaces. CCFS beams that exhibited

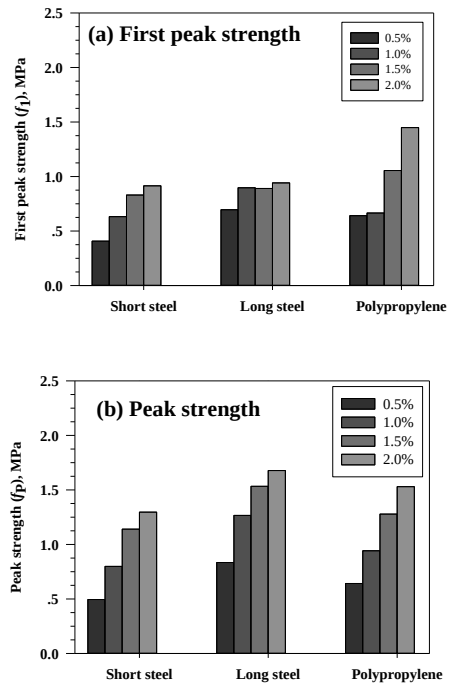


Figure 4. Effect of fiber type on (a) first peak strength and (b) peak strength at different fiber contents

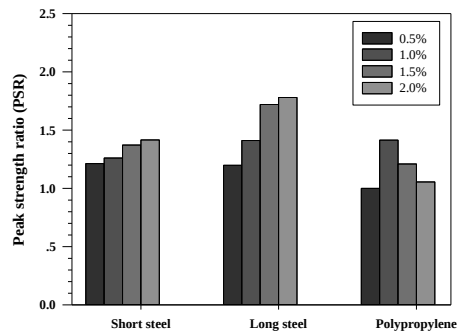


Figure 5. Effect of fiber type on peak-strength ratio (PSR) at different fiber contents

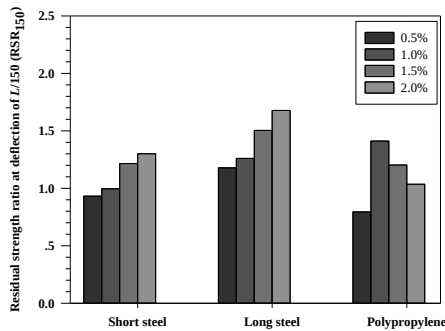


Figure 6. Effect of fiber type on the residual strength ratio at a deflection of L/150 (RSR150) at different fiber contents

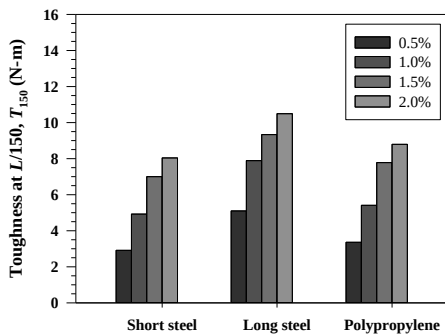


Figure 7. Effect of fiber type on the toughness at a deflection of L/150 (T_{150}) at different fiber contents

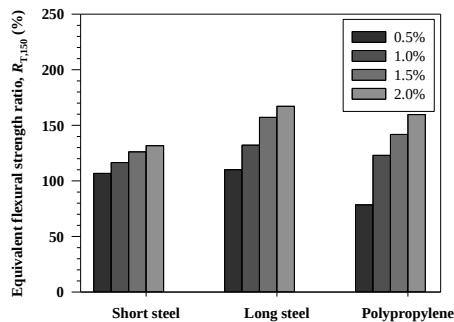


Figure 8. Effect of fiber type on the equivalent flexural ratio ($R_{T,150}$) at different fiber contents

deflection- hardening behavior performed better in toughness than those exhibiting deflection- softening behavior because they absorbed more energy after cracking. Therefore, long steel fiber is able to absorb the largest amount of T_{150} when compared to the CCFS with other fiber types. Short steel fiber, long steel fiber, and polypropylene fiber provided values in the range from 3 to 8, 5 to 11, and 3.5 to 8.5 N-m, respectively.

Equivalent Flexural Strength Ratio

Figure 8 clearly shows that all softening and hardening CCFSs provided $R_{T,150} < 100\%$ and $R_{T,150} > 100\%$, respectively. $R_{T,150}$ increased with the increasing fiber content for short steel, long steel, and polypropylene fibers and had the highest values of 135, 170, and 160%, respectively, at a 2% fiber content. Thus, long steel fiber provided the best performance in terms of $R_{T,150}$. Considering the 2% fiber content, long steel fiber provided better performance than the CCFSs with short steel and polypropylene fibers by factors of approximately 1.25 and 1.06, respectively.

Concept of Overall Performance of CCFS

To decide which fiber type is the best for use in CCFS, the concept of overall performance must be introduced to provide a general idea regarding the comparative performance of fiber types. The overall performance of CCFS was divided into 5 sub-design performances, as presented in previous sections: (1) peak strength (f_p), (2) peak strength ratio (PSR), (3) residual strength ratio at a deflection of L/150 (RSR_{150}), (4) toughness at a deflection of L/150 (T_{150}), and (5) equivalent flexural strength ratio ($R_{T,150}$). The concept used for the determination of overall performance of a CCFS is described as follows:

- a) Calculate the average sub-performance value for each fiber type, as tabulated in Table 2, which is defined as:

Table 2. Average sub-performance values for each fiber type

Fiber type	Sub-performance of CCFS				
	P_p (kPa)	PSR	RSR ₁₅₀	T ₁₅₀ (N-m)	R _{T,150}
Short steel	0.93	1.32	1.11	5.72	120
Long steel	1.33	1.53	1.40	8.20	142
Polypropylene	1.10	1.17	1.11	6.33	126

Table 3. Comparative score of the sub-performance for each fiber type based on a full score of 100

Fiber type	Sub-performance of CCFS				
	P_p	PSR	RSR ₁₅₀	T ₁₅₀	R _{T,150}
Short steel	70	86	79	70	85
Long steel	100	100	100	100	100
Polypropylene	83	76	79	77	89

Table 4. Rank of the effectiveness of each fiber used in this study based on an overall performance rating

Rank	Fiber type	Average percentage of overall performance	Overall performance rating
1	Long steel	100	Excellent
2	Polypropylene	81	Very good
3	Short steel	78	Good

$$\text{Average sub performance value} = \frac{\text{Sum of performance values}}{\text{Number of fiber contents}} \times 100$$

(3)

$$\text{Percentage overall performance} = \frac{\text{Sum of score of sub performance}}{\text{Sum of full score of sub performance}} \times 100\%$$

(5)

b) Calculate the comparative score of the sub-performance for each fiber type based on a full score of 100 as shown in Table 3, which is defined as:

$$\text{Comparative score} = \frac{\text{Average sub performance value}}{\text{best average sub performance value}} \times 100$$

(4)

c) Calculate the percentage of overall performance, as shown in Table 4, which is defined as:

The overall performance rating was divided into 7 levels: (1) excellent, (2) very good, (3) good, (4) fairly good, (5) fair, (6) poor, and (7) very poor. Because there was no standard to define these levels, the common concept of significance in geotechnical engineering was adopted (Jamsawang *et al.*, 2015b), as listed in Table 5. Table 4 shows the ranks of all fiber types based on the overall performance of CCFS (%). It can be observed that only the long steel fiber provides excellent overall performance, whereas the polypropylene gives very good performance. In addition, the short steel fiber achieved good performance.

Conclusions

This research was performed as a comparative study of the effect of fiber type on the flexural performance of compacted cement-fiber-sand (CCFS), according to ASTM C1609/C1609M (ASTM, 2012). Three fiber types were studied: short steel, long steel, and polypropylene fibers. The fiber contents were 0.5 to 2% by volume, and the cement content was fixed at 5% by dry weight. Based on the experimental results, the following conclusions are drawn:

(1) Fiber type affects the behavior in which CCFSs respond to loading. Steel fibers exhibit a hardening response independent of fiber content, whereas polypropylene fibers exhibit a fiber-content-independent softening response. From the cost point of view, steel fiber is recommended in terms of attaining a hardening response at the lowest fiber content of 0.5%.

(2) The concept of comparative overall performance is introduced to select and rank reasonably suitable fiber types for use as CCFSs for pavement materials. This approach is chosen because it takes into account the main sub-flexural performance categories. Due to having the highest score in all performance types, the long steel fiber has the only rating of excellent in overall flexural performance. The polypropylene and short steel fibers provide the high scores in some sub-performance types, resulting in ratings of very good and good in overall flexural performance, respectively.

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