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Article

Fibre-Reinforced Polymer Made from Plastic Straw for Concrete Confinement: An Alternative Method of Managing Plastic Waste from the COVID-19 Pandemic

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Abstract. Plastic pollution is one of the most significant environmental issues worldwide. During Covid-19 pandemic, single-use plastic containers have been overused due to a lock-down policy. This led to remarkable increase in municipal plastic wastes. An alternative method to manipulate plastic wastes is to recycle them as construction and building materials. The research introduces an idea of using plastic straw to produce fibre-reinforced polymer composite as a strengthening material to confine concrete. The plastic straw fibre-reinforced polymer composite coupons were tested to obtain their tensile strength, ultimate strain, and elastic modulus. A series of compression tests were conducted on plastic straw fibre-reinforced polymer composite confined concrete to investigate the improved strength and ductility performance. The results show that the mechanical properties of plastic straw fibre-reinforced polymer composite are acceptable for concrete strengthening purpose. More importantly, use of plastic straw fibre-reinforced polymer composite is rewarded by its environmental solution for reduction of plastic wastes in household.

Keywords: Fibre-reinforced polymer, concrete confinement, plastic straw, waste management, COVID-19.

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1. Introduction

1.1. Waste Situation

Plastic pollution is one of the most crucial environmental problem worldwide. Plastic pollution can afflict both lands and oceans, in which more than million tonnes of plastic waste pollute the sea and ocean every year [1]. In Thailand, there is approximately 2 million tonnes of plastic waste per year with only 0.5 million tonnes of plastic recycled. The remaining 1.5 million tonnes of single-use plastics (SUPs) such as bags, straws, and food containers are hardly recycled owing to difficulty in collection, sorting wastes, cleaning, and complicated recycling process. As a result, they are often landfilled with other solid wastes, triggering other serious problems as landfill impels more spaces and higher budget than other waste management such as incineration [2]. Governmental sectors are also responsible for disposing a large amount of plastic wastes each year (Fig. 1) as they have caused millions more pieces of SUPs such as plastic bags, cups and foams during January to June 2020 (Fig. 2). As a result, the Thai cabinet conference on 17 April 2019 recognised the Roadmap on Plastic Waste Management during 2018-2030 in order to reduce and prevent the use of plastic, while replacing it with environmentally friendly materials [3]. Since 2017 Chulalongkorn University has launched a "Zero-waste strategy", involving reduction, reusing, and recycling, as known as 3Rs concept. This concept becomes a university's successful mission to diminish number of SUPs in the campus [4].

Fig. 1. Plastic wastes disposed in governmental sectors, Thailand.

However, during the COVID-19 pandemic in 2020, the use of SUPs has remarkably aggravated since people tend to use take-home foods and beverages due to prohibition of eat-in service. Moreover, people prefer food delivery services along with online shopping platforms due to a lock-down policy. Following the statistics recorded by Thailand Environment Institute [5], the average number of plastic wastes significantly rose from 2,120 tons per day in 2019 to relatively 3,440 tons per day during January and April in 2020, claiming nearly 62% increase. This is because only one individual delivery could multiply plastic products such as food containers, beverage holders, straws, chopsticks, spoons, forks, seasoning packets and more. With an unclear information on virus's spreading mechanism, a global fear from potential contaminated surfaces has also ignited increase in demand of SUPs.

Fig. 2. Number of plastic wastes disposed in Thai governmental offices (Data collected by Pollution control department from January to June 2020).

In a global scale, consumption of SUPs during the pandemic is expected to increase by 40% for plastic package and 17% for other applications, including medical uses since safety assurance becomes highly strict to reduce spreading of the Coronavirus [6]. As viable vaccine to prevent COVID-19 is still under meticulous development by researchers, the coronavirus continuously spreads across the world, threatening not only people's lives but also global environment. The upsurging use of SUPs by billions of humans on earth is rapidly accelerating an emerging environmental issue. Notwithstanding, the recycling alternatives of SUPs should be the solution to unlock the global environmental impact for future generation.

1.2. Use of Plastic Wastes in Construction

One of the effective approaches to remarkably reduce plastic wastes is recycling them as alternative materials in the construction industry since it demands the large amount of materials. To assure safety and applicability of plastic wastes in construction industries, their mechanical and durability performances must fulfil for the required application. To date, many researchers have attempted to use recycled plastic wastes in plastic aggregates as a partial or full replacement of natural aggregates. Hama and Hilal [7] successfully developed the self-consolidating concrete (SCC) mixed with plastic wastes as fine aggregate. Their study indicated that the fresh properties of SCC such as flow and filling ability can be enhanced when adding plastic fine aggregate at 12.5% by weight. In lightweight concrete, Alqahtani et al. [8] and Castillo et al. [9] investigated applicability of recycled plastic to substitute natural coarse aggregates. They revealed that the fresh and mechanical properties (e.g., slump, compressive strength, flexural strength, splitting tensile strength and elastic modulus) reduced when additionally replaced natural aggregate with more plastic waste. Recently, Belmokaddem et al. [10] investigated the effect of replacement both fine and coarse aggregates with some plastic wastes; polypropylene (PP), high-density polyethylene (HDPE), and polyvinylchloride (PVC) based. They found that plastic waste could significantly decrease the density while improving acoustic insulation characteristics in concrete.

In addition to replacing natural aggregate using plastic aggregate (PA), several types of plastic wastes were employed as a short fibre mixed in fibre reinforced concrete (FRC). Khalid et al. [11] conducted experiment of recycled polyethylene terephthalate (PET) bottle and synthetic waste wire in FRC. Their experimental results indicated that pull-out strengths of synthetic fibres in a concrete matrix could enhance remarkably with high volume of fibres as well as irregular fibre's shape. Then, they also extended their study on a ring-shaped PET-FRC in structural beam [12]. Although they concluded that plastic fibres included to concrete rarely exhibited any significant influence on the failure mode, it significantly improved the structural performances of the beams with regard to initiation of first crack and ultimate strength. In addition, Mohammed and Rahim [13] proposed the use of recycled PET in FRC with high strength concrete, showing the improved cracking resistance due to PET fibre. Forti and Lerna [14] also conducted experiment on waste PET aggregates mixed in mortar and they successfully improved its strength.

1.3. Alternative FRP

As existing concrete structures are usually deteriorated and damaged throughout their life services, strengthening them to improve structural performances is necessary to assure safety. Fibre Reinforced Polymer (FRP) is considered as one of the popular strengthening materials since it has lightweight and high corrosion resistance. The commonly used FRPs are Carbon FRP (CFRP), Aramid FRP (AFRP) and Glass FRP (GFRP) which are costly for local non-engineering buildings with negative impact on environment, igniting demand for alternatively eco-friendly FRP materials. To date, there have been many eco-friendly FRP materials such as natural FRP (Jute, Hemp, Cotton) and recycled waste FRPs (PEN-FRP, PET-FRP, Vinylon fibre ropes, and ultra-high molecular weight polyethylene (UHMWPE) tape) [15-20]. From Jirawattansomkul et al.'s experimental investigation [15,17], those eco-friendly FRPs as confining materials could provide promising strength enhancement for confined concrete members, while improving their ductility. Similarly, Dai et al.'s studies [18-19] used large rupture strain PEN- and PET- FRPs for strengthening and found that they enhanced remarkably the displacement ductility of concrete members both under monotonic and seismic loading. In addition, Vinylon fibre ropes and UHMWPE tapes developed interesting resilience features as they can reach high portion of their confining efficiency even after their fracture initiation [20]. Although both natural and recycled waste FRPs have successfully replaced conventional FRPs, strengthening of concrete using FRPs made from SUP wastes such as plastic straws are still rare. Instead of direct disposal of these SUP wastes, they can be produced as an alternative FRP material. This in turn helps to reduce the large amount of SUP wastes used each year, leading to a positive impact on both terrestrial and marine environment.

2. Materials and Methods

Plastic straws (PSs) from plastic wastes especially special straws for bubble-milk tea are one of the most consumed SUPs, especially during Covid-19 pandemic because many restaurants and shops encourage take-home beverages. As a result, greater number of used PSs has become an emerging problem of contaminated marine [6]. To eliminate PS wastes, the research programme thus involves production of recycled plastic straw (PS) as fibre reinforced composites, investigations of the mechanical and microscopic properties of plastic straw fibre reinforced polymer (PSFRP) composites and compressive tests of PSFRP-confined concrete cylinders.

2.1. Production of PSFRP

The manufacturing process of plastic straw FRP (PSFRP) is summarised in Fig. 3. Firstly, the used plastic straws (PSs) were collected from the university's canteen, and then they were cleaned using soapy water. All clean PSs were wiped by clean cloth and air dried for 7 days. Then, the PSs with a hollow cylindrical shape were cut into half in the longitudinal direction and spread to have the rectangular shape. The rectangular PSs were sewed together using a hand-made sewing machine to make PS sheets with the intended dimension. The final product of PS fabric sheets and wrapping of PSFRP on concrete cylinder are presented in Fig. 3. Based on actual consumption in the university's canteen, two groups of PSs (Groups A and B in Fig. 4(a)) were selected depending on quality, colour and usage. The single straw was cut in half with a dimension of 20 × 240 mm as a common length of typical used PSs. The PSs in Group A with a transparent colour were softer and lighter than that in Group B with solid colour, in which PSs in Group A is more usage in the local markets.

To produce the PS sheet, PSs with 240 mm in length along the horizontal direction were imbricated between two adjacent straws with the overlapping length of 10 mm. As required wrapping length of 440 mm, two PS sheets were conjoined by sewing with the overlapping length of 40 mm in the vertical direction (Fig, 4(b)). The final dimension of one wrapping PS sheet became 200 × 440 mm which mainly contains a total of 40 pieces of used PSs.

Fig. 3. Manufacturing process of PSFRP from plastic-straw wastes.

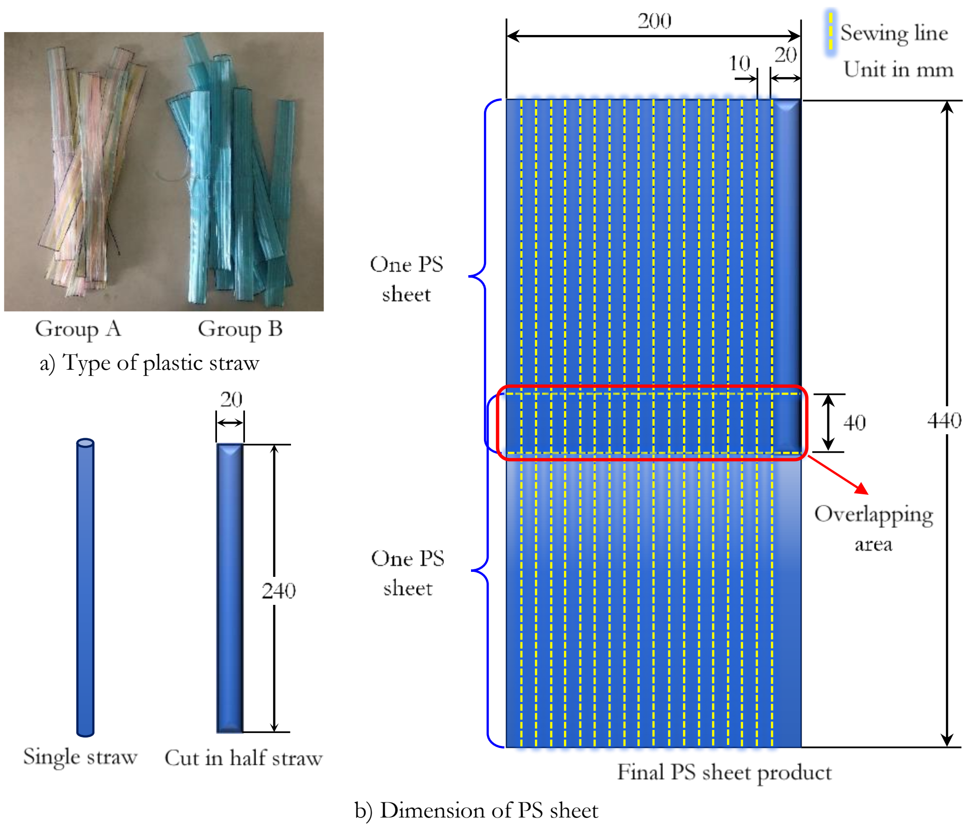


Fig. 4. Details of PS sheet.

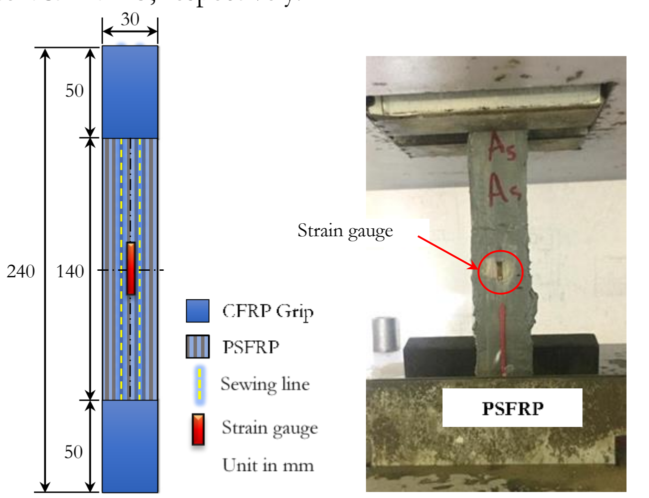
Table 1. Tensile properties of PSFRP coupon specimens.

Group	Specimen	Tensile strength (MPa)	Initial elastic modulus, E_1 (MPa)	2nd stage elastic modulus, E_2 (MPa)	Rupture strain (%)
A	PSFRP-A1	9.28	1,156	652	2.48
	PSFRP-A2	10.07	1,431	152	3.98
	PSFRP-A3	11.76	1,630	214	4.22
	Average	10.37 ± 0.73	1,406 ± 138	339 ±157	3.56 ± 0.54
B	PSFRP-B1	9.28	2,287	504	0.59
	PSFRP-B2	11.98	2,814	158	1.16
	PSFRP-B3	11.53	1,662	502	1.24
	Average	10.93 ± 0.84	2,254 ± 333	388 ± 115	1.00 ± 0.21

Note: Statistical data are shown as the mean ± standard error (SE).

2.2. Tensile Test of Coupon Specimens

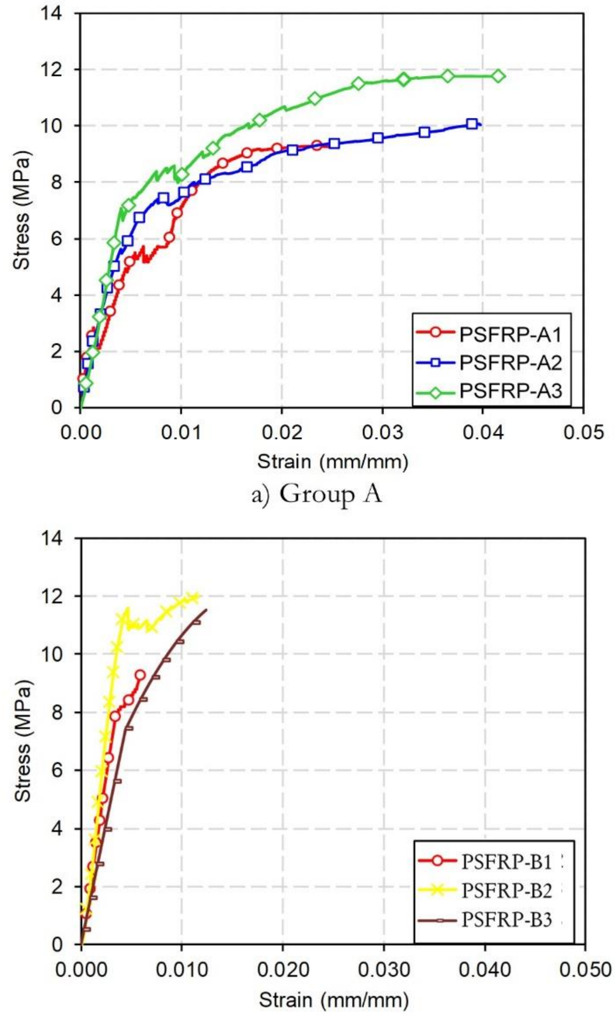
A total of six PSFRP coupon sheets having a density of 0.87 g/cm³ with a thickness of 0.12 mm were prepared using wet-layup method, as summarised in Table 1. The density of PS sheet was measured by a gas pycnometer with a unit of weight per volume, while the weight per unit area of the fabric was measured by a weight scale (accuracy of 10 mg). Then, the thickness of PS sheet was calculated from the weight per unit area divided by its density. Coupon specimens were cut into a dimension of 30 mm × 240 mm (see Fig. 5(a)) using three pieces of PSs per specimen. Following by the wet layup process, fibre sheets were impregnated with an epoxy resin, consisting of two-component resins mixed with the base to hardener ratio of 2:1 by weight, to form the PSFRP composites. The epoxy resin with a viscosity of 2,000 cps at 26 °C performed a good compromise integrity between PS and resin. The CFRP grips (30 mm wide and 50 mm long) were then attached onto the two ends of each PSFRP coupon to avoid stress concentration at grip areas due to the loading during a tensile test. Then, all coupon specimens were cured in a laboratory environment for 7 days. The PSFRP coupons were categorised into Groups A and B with labelling as PSFRP-A1 to PSFRP-A3 and PSFRP-B1 to PSFRP-B3, respectively.



a) Details of PSFRP coupon specimen b) Coupon test of PSFRP specimen

Fig. 5. Tensile test of PSFRP coupon specimens.

To acquire their tensile strength, ultimate strain, and elastic modulus, the PSFRP coupons were then tested following the JSCE-E541 standard [21] using universal testing machine (UTM) with a displacement control at the loading rate of 2.0 mm/min. During the tensile test, the strains of PSFRP coupons were recorded using strain gauges attached at the midpoint of specimens, as shown in Fig. 5(b).



a) Group A

b) Group B

Fig. 6. Stress-strain relationships of PSFRP coupons.

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As depicted in Fig. 6, the tensile stress-strain relationships of PSFRP coupons in both Groups A and B exhibited nonlinear behaviour. It can be observed that the tensile strength of PSFRP-A (10.37 ± 0.73 MPa) was almost similar to that of PSFRP-B (10.93 ± 0.84 MPa). Meanwhile, PSFRP-A resisted a higher ultimate tensile strain (3.56 ± 0.54 %) compared to that in PSFRP-B (1.00 ± 0.21 %). This in turn leaded to smaller elastic modulus in PSFRP-A. Table 1 reports the tensile properties of all PSFRP coupons (e.g., tensile strength, initial elastic modulus (E_1), 2nd stage elastic modulus (E_2), and ultimate strain). Since PSFRP-A developed compromising ultimate tensile strain, the PS sheets produced using PS from Group A (see Fig. 4(a)) were then used for strengthening of concrete cylinder. The failure patterns of PSFRP in both Groups A and B are presented in Fig. 7 where the failure area occurred around the mid-point of PSFRP coupon specimens.

To identify the composition of recycled PSs, X-Ray Diffraction (XRD) was conducted for PS wastes produced in PSFRP-A. From XRD result in Fig. 8, the patterns of crystalline structure indicates that the recycled PS waste was Polyethenylbenzene, as known as $(C8H8)_n$, which is considered as the precursor to polystyrene. The Polyethenylbenzene is commonly used in food packaging such as cups and plate because its acute toxicity to animal is relatively low [22].

The scanning electron microscope (SEM) was performed on PSFRP coupons at the ultimate load to observe the microfibril, surface topography, cross-section of PSFRP coupons in Group A. Figure 9 demonstrates the SEM results of PSFRP in which the left and right images are at 120x and 250x magnification. It can be observed that the cohesion between the PSFRP sheet and the matrix was poor, hindering proper stress transfer among PS sheets. This unwell integrity between PS sheets and matrix at the ultimate stage is attributed to the slippery surface of PSs, leading to delamination between PSFRP layer. However, such integrity between PSFRP matrix at the service stage was well functioned. This also indicates that the suitable epoxy resin as the matrix of PSFRP composites should properly applied on PS sheets.

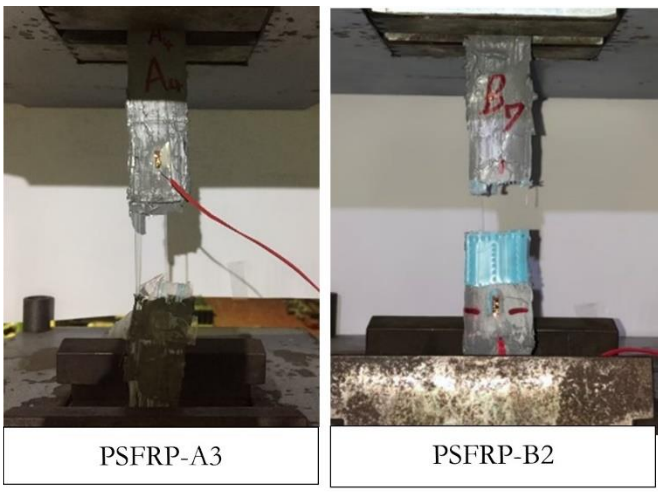

Fig. 7. Failure patterns of PSFRP coupons.

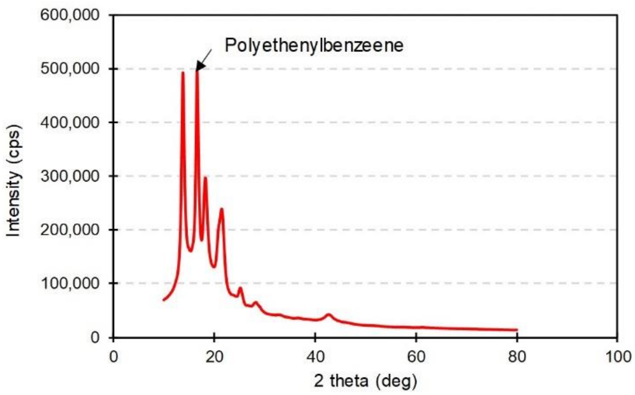

Fig. 8. XRD patterns of PS wastes used for PSFRP in Group A.

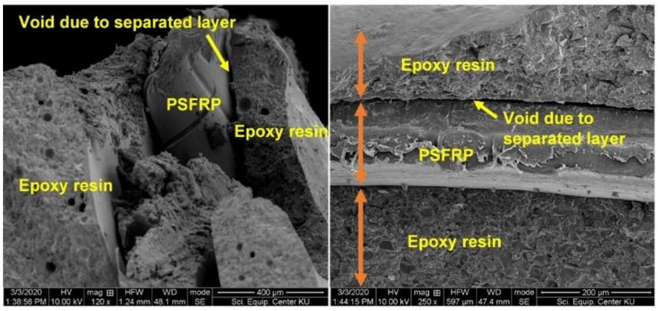

Fig. 9. SEM results of PSFRP coupons in Group A.

2.3. Compression Test

To investigate the effect of PSFRP confinement on both normal and low strength concretes (NSC and LSC groups), a total of 24 cylindrical concrete specimens with a diameter of 100 mm and a height of 200 mm (Fig. 10(a)) were prepared. The concrete mix proportion is reported in Table 2, where the compressive strength was equal to 33.1±1.25 MPa and 7.69±0.77 MPa for both NSC and LSC, respectively. In this study, the testing parameters are concrete strength and the number of PSFRP layer (1 to 3 plies). Control specimens in each series were denoted as NSC-1 to NSC-3 and LSC-1 to LSC-3. Meanwhile, confined concrete specimens in each series were suffixed by number of PSFRP plies from 1 to 3 plies (PS1 to PS3), as summarised in Table 3. Taking NSC-1 and NSC-PS1-1 as examples, NSC-1 refers to the NSC specimen without PSFRP jacketing, whereas NSC-PS1-1 refers to the NSC specimen jacketed with 1 ply of PSFRP.

Prior to jacketing PSFRP around concrete cylinders, the small voids on the concrete's surface was filled by applying primer on the surface and the void-filled concrete specimens were later cured for 24 hours in the ambient laboratory environment. Then, epoxy resin was impregnated into the PS sheet for each concrete specimen at 7 days curing period. The continuous PS sheet was wrapped along the transverse direction of the concrete cylinder with an overlapping length of approximately 125 mm (see Fig. 10(b)) which is slightly less than that recommended in Pimanmas et al. [23] and Jirawattanasomkul et al. [17]. This is because of the available wasted plastic straws were shorter than

Table 2 Details of the concrete mix proportion.

Group	Compressive strength at 28 days (MPa)	W/C (-)	Water (kg/m³)	Cement (kg/m³)	Coarse aggregate (kg/m³)	Fine aggregate (kg/m³)
NSC	33.1±1.25	0.49	200	408	1,008	701
LSC	7.69±0.77	0.78	200	256	1,070	827

Note: NSC is normal strength concrete and LSC is low strength concrete.

Table 3 Summary of experimental results for compression test.

Group	Specimen	Confining layer (ply)	t_{FRP} (mm)	f'_{co} (MPa)	f'^{*}_{cc} (MPa)	$f'^{*}_{cc-average}$ (MPa)	Increased strength (%)	$\varepsilon_{h,rup}$ (%)
Low strength (LSC)	LSC-1	-	-	8.65	-	8.72 ± 0.04	-	-
	LSC-2			8.78				-
	LSC-3			8.74				-
	LSC-PS1-1	1	0.12	-	8.87	8.56 ± 0.31	-1.85	0.25
	LSC-PS1-2		0.12		N/A			N/A
	LSC-PS1-3		0.12		8.25			0.22
	LSC-PS2-1	2	0.24	-	10.04	9.49 ± 0.53	8.75	0.16
	LSC-PS2-2		0.24		10.01			0.49
	LSC-PS2-3		0.24		8.42			0.09
	LSC-PS3-1	3	0.36	-	11.29	11.2 ± 0.43	28.37	0.41
	LSC-PS3-2		0.36		11.91			0.13
	LSC-PS3-2		0.36		10.41			0.48
Normal strength (NSC)	NSC-1	-	-	32.15	-	32.76 ± 0.44	-	-
	NSC-2			33.61				-
	NSC-3			32.51				-
	NSC-PS1-1	1	0.12	-	36.89	33.54 ± 2.18	2.41	0.37
	NSC-PS1-2		0.12		34.29			0.25
	NSC-PS1-3		0.12		29.46			0.32
	NSC-PS2-1	2	0.24	-	34.13	35.63 ± 1.54	8.78	0.23
	NSC-PS2-2		0.24		34.05			0.31
	NSC-PS2-3		0.24		38.71			0.50
	NSC-PS3-1	3	0.36	-	39.84	38.86 ± 1.61	18.63	0.60
	NSC-PS3-2		0.36		41.01			0.41
	NSC-PS3-3		0.36		35.72			0.22

N/A is not applicable due to premature failure of the specimen prior to load test. Statistical data are shown as the mean ± standard error (SE). The SE is calculated from standard deviation divided by square root of number of samples.

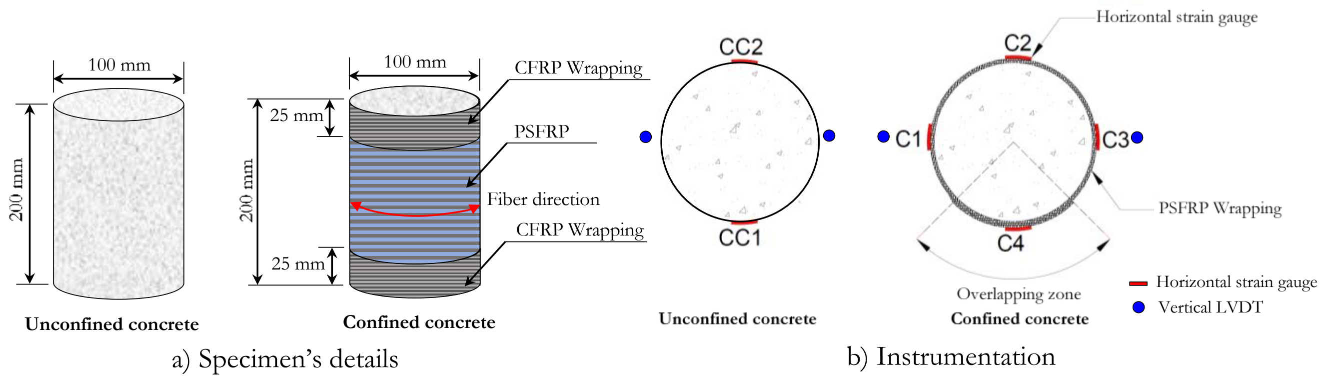

Fig. 10. Details of concrete cylinder specimens and instrumentation.

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the natural fibres. To measure the lateral strains of unconfined control specimens, two horizontal strain gauges for concrete (labelled as CC1 and CC2) with an accuracy of 10 $\mu\varepsilon$ were mounted on the specimens at 180° apart at their middle height as presented in Fig. 10(b). On the other hand, for PSFRP-confined concrete, four horizontal strain gauges (labelled as C1 to C4) with an accuracy of 10 $\mu\varepsilon$ were attached on the PSFRP's surface in the middle height of specimens at every quarter of circumference to measure their lateral strains. Two Linear Variable Differential Transducers (LVDTs) with a resolution of 0.01 mm were set in a compressometer to measure the axial shortening as illustrated in Fig. 11.

The concentric monotonic compression test by Universal Testing Machine (UTM) was conducted in accordance with JIS A 1108 [24] under displacement control and with a loading speed of 1.0 mm/min until failure (see Fig. 11). Table 3 summarises the details of all unconfined and confined concrete specimens as well as key experimental results.

Fig. 11. Test setup and instrumentation of compression test (Specimen LSC-PS1-1).

3. Results and Comparisons

3.1. Failure Modes of Confined Concrete

Failure modes of unconfined and PSFRP-confined concrete cylinders in NSC and LSC series are illustrated in Fig. 12. Overall, confined cylinders failed by rupture of PSFRP which gradually developed without loud noise at the ultimate state. The initiation of PSFRP rupture can be seen outside the overlapping zone from either the top or the bottom of specimens. The delamination between PSFRP and epoxy resin could be observed in some specimens, indicating disintegrating of PSFRP and matrix. Although it is difficult to indicate the effect of PSFRP confinement on the failure modes of concrete with different compressive strengths, the significant enhancement of compressive strength as well as ultimate axial strain of concrete can be observed.

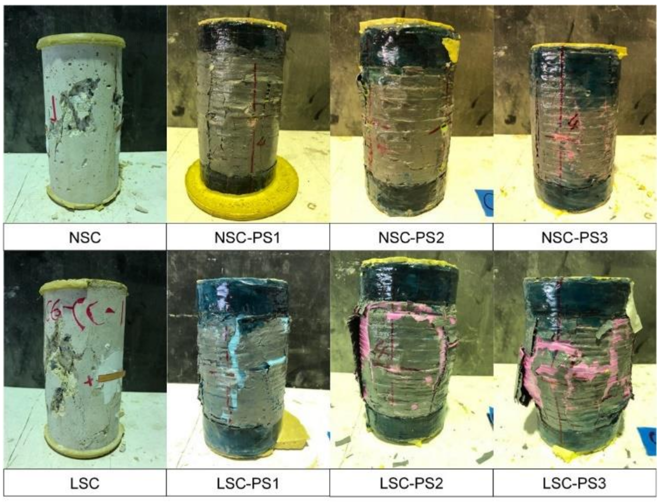


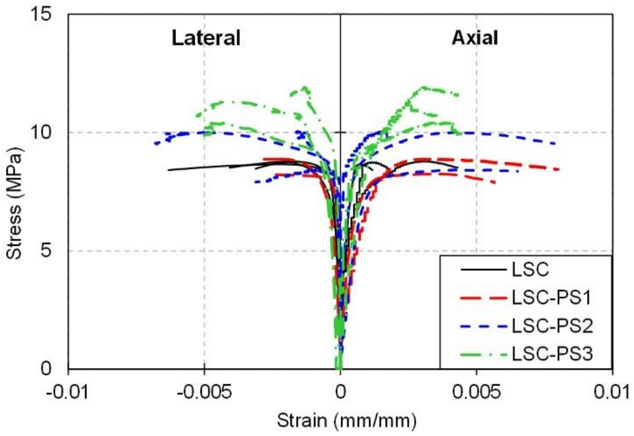
Fig. 12. Failure modes of concrete cylinder specimens.

3.2. Compression Stress-Strain Relationships of Confined Concrete

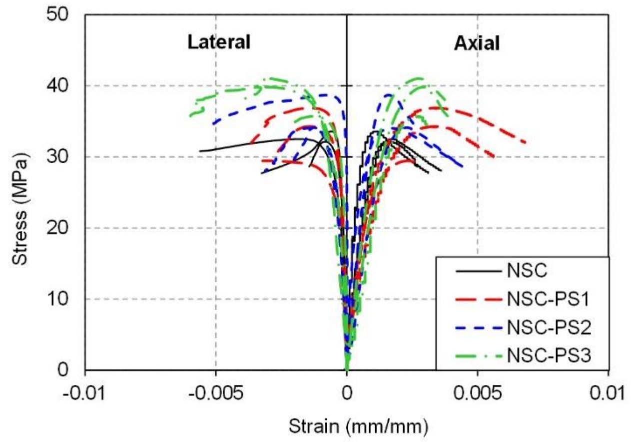
Figure 13 illustrates both lateral and axial stress-strain relationships for unconfined and confined concrete specimens with normal and low strengths under compression test, respectively. The lateral strains are presented in negative values, whereas the axial strains are presented in positive values. In the case of NSC, the stress-strain relationships of PSFRP confined concrete exhibited a linear ascending behaviour followed by quick softening (i.e., the descending curve dropped abruptly after the peak). In the case of LSC, the stress-strain curves exhibited a parabolic shape with a nonlinear ascending part followed by a gradual softening part. The overall trend is different from the bilinear manner as observed in conventional FRP-confined concrete. When more plies of PSFRP were applied, larger ultimate axial strains were developed, leading to larger compressive strengths as well. It should be noted that delamination between PSFRP plies occurred in specimens LSC-PS3 and NSC-PS3, causing relatively low axial and lateral strain development. However, the specimen LSC-PS1-2 was prematurely failed, leading to termination of the test.

3.3. Strength Enhancement

The enhancement of compressive strength for both LSC and NSC is reported in Table 2 and Fig. 14. It can be observed that the confinement of PSFRP improved the compressive strength of concrete in a range of 2.41% to 28.37%. The increased strength varied from 8.75% to 28.37% in the LSC group, while from 2.41% to 18.63% in the NSC group. This indicates that PSFRP confinement contributes a larger strengthening effect for low strength concrete. With 3 plies of PSFRP composite, the compressive strength could develop as high as 11.2 MPa and 38.86 MPa for LSC and NSC specimens, respectively. This may be because the effect of confinement from 3-ply PSFRP jackets is more effective than that of concrete with smaller amount of PSFRP plies. To compare the strength enhancement due to PSFRP and other FRPs, the experimental results of Jute FRP (JFRP) confinement by Jirawattanasomkul et al. [15] are taken with the increased strength in a range of 3.59% to 13.11%. With applying same FRP volumetric ratio of FRP (ρ_f = 1.44 %), the strength enhancement of PSFRP-confined concrete (28.37%) is higher than that of JFRP confinement (10.72%) in case of normal concrete strength, showing good applicability of PSFRP. Note that FRP volumetric ratio (ρ_f) for fully wrapped circular concrete is defined as $\rho_f = 4 \times t_{FRP}/D$, where t_{FRP} is FRP's thickness and D is the diameter of concrete cylinder.



a) Low strength concrete



b) Normal strength concrete

Fig. 13. Stress-strain relationship of unconfined and PSFRP-confined concrete cylinder specimens.

3.4. Hoop Rupture Strains of PSFRP

Concerning impact of PSFRP layers with regard to a hoop rupture strain, the hoop strain of PSFRP-jacketed concrete measured on the outer PSFRP's layer are presented in Fig. 15. When increased higher layers of PSFRP, the hoop strain at rupture stage slightly increased from 0.23% to 0.34% and from 0.31% to 0.41% for LSC and NSC, respectively. As the hoop strains can only be obtained from strain gauges attached at the outer plie of PSFRP, the outer layer initially ruptured while the inner layers have not yet been fractured, resulting in further propagate of hoop strain. Meanwhile, the delamination between PSFRP's layer at the inner layer occurred after initiation of PFRP rupture at outer layer.

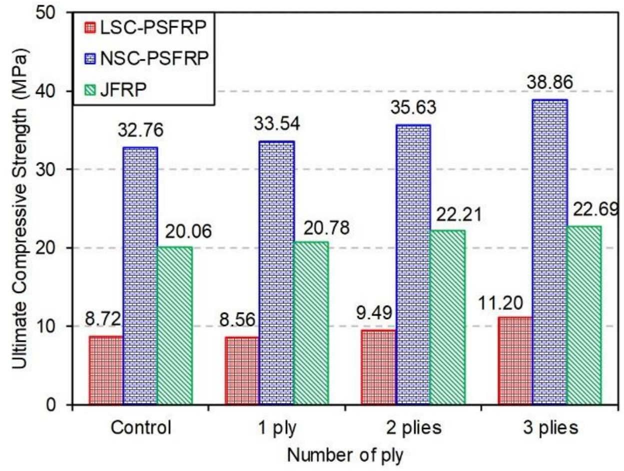


Fig. 14. Strength enhancement of PSFRP-confined concrete cylinder specimens.

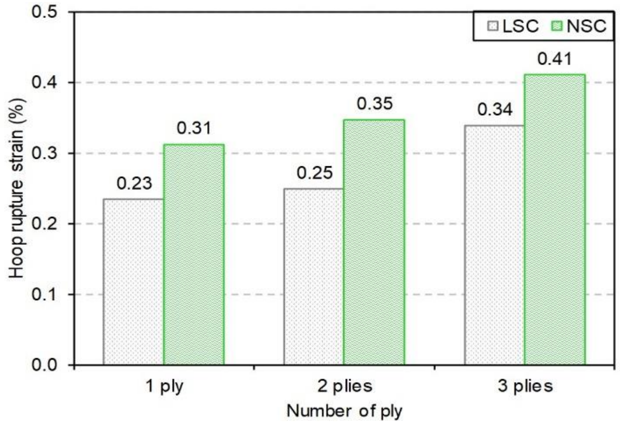


Fig. 15. Effect of PSFRP's layer on hoop rupture strain.

4. Calculation of PS waste consumption and a Case Study

It is important to estimate the waste reduction of using PS sheets as an FRP strengthening material. The reduction of PS wastes through recycling as PSFRP was then evaluated by calculating the decreased number of PS wastes as reported in Table 4. As the required strengthening area of cylinder concrete both LSC and NSC is approximately equal to 3.16 m^2, the total amount of recycled PS becomes 1,440 straws. This in turn reduces PS wastes around 455 straws/m^2. In the actual strengthening for reinforced concrete (RC) columns, it usually requires more strengthening areas than that in a small-scale concrete cylinder test, implying more demand of PS wastes. Therefore, in practice the amount of PS wastes could be significantly reduced through recycling of PS as FRP material.

To demonstrate PSFRP for strengthening in existing buildings, a case study of structural building damages due to a strong earthquake in the northern Thailand is illustrated in this section. The 2014 Mae Lao Earthquake caused several building damages since most of building structures were insufficiently designed against seismic response [25-26]. RC columns damaged during the 2014

Table 4 Waste reduction from recycling plastic straw to PSFRP.

Group	Strengthening details for one cylinder			Total used PSFRP sheet		Amount of recycled plastic straw	Unit weight of straw	Recycled plastic straw waste per area	
	Length (mm)	Height (mm)	Area (m^2)	Amount (sheet)	Area (m^2)	(straw)	(kg/straw)	Amount straw/m^2	Weight kg/m^2
LSC-PS	440	200	0.088	18	1.58	720	0.0004	455	2.77
NSC-PS	440	200	0.088	18	1.58	720	0.0004	455	2.77
Total	-	-	-	36	3.16	1,440	-	-	-

Table 5 A case study of applying PSFRP for strengthening RC columns.

Details	unit	Building No.1	Building No.2	Building No.3	Building No.4	Total amount (straw)
Field inspection						
First Floor Column Area (A_{column})	m^2	2.3	3.2	3.2	5.2	-
First Floor Column - Existing tie reinforcement ratio (ρ_{si})	%	0.3	0.6	0.6	0.18	-
Damage due to Mae Lao Earthquake (2014)	-	Moderate	Severe	Severe	Severe	-
General column details						
Column width (b)	m	0.20	0.30	0.30	0.30	-
Column height (h)	m	0.20	0.50	0.50	0.45	-
Gross area (A_g)	m^2	0.04	0.15	0.15	0.14	-
Area of core concrete inside tie reinforcement (A_{ch})	m^2	0.03	0.12	0.12	0.11	-
Concrete cover	m	0.02	0.02	0.02	0.02	-
Spacing of tie bar (s)	m	0.2	0.2	0.2	0.27	-
Type of tie bar	-	Deformed bar	Deformed bar	Deformed bar	Round bar	-
Diameter of tie bar	mm	9	9	9	6	-
Compressive strength of concrete (f'_c)	MPa	25	25	25	25	-
Yield strength of tie bar (f_{yh})	MPa	300	300	300	240	-
Required reinforcement ratio in transverse direction (DPT-seismic design [28])						
$\rho_{sh1} = 0.3\times(f'_c/f_{yh})\times[(A_g/A_{ch})-1]$	%	10.66	9.84	9.84	11.73	-
$\rho_{sh2} = 0.09\times(f'_c/f_{yh})$	%	0.75	0.75	0.75	0.94	-
Required tie reinforcement ratio, $\rho_{sh} = \min(\rho_{sh1}, \rho_{sh2})$	%	0.75	0.75	0.75	0.94	-
Required PSFRP strengthening						
Required additional PSFRP reinforcement ratio (ρ_f)	%	0.45	0.15	0.15	0.76	-
Thickness of PSFRP (t_{PSFRP})	mm	0.12	0.12	0.12	0.12	-
Required PSFRP layer (n_{PSFRP})	layer	8	3	3	12	-
Needed straws for PSFRP strengthening of columns (455 straws/m^2)	straw	**7,849**	**3,640**	**3,640**	**28,004**	**43,133**

* Needed straws for PSFRP strengthening of columns is calculated by $A_{column} \times n_{PSFRP} \times$ (455 straws/m^2).

Mae Lao Earthquake were taken after inspection of 4 school buildings by Lukkunaprasit et al. [27]. In this study, the first-floor columns with a total area between 2.3 m^2 to 5.2 m^2 were both moderately and severely damaged owing to insufficient tie reinforcement (with a tie reinforcement ratio (ρ_{si}) of 0.18% to 0.60%). Then, the required reinforcement ratio in the transverse direction (ρ_{sh}) is calculated based on DPT-1302 for seismic design [28]. With general details of columns reported in Lukkunaprasit et al. [27], the required ρ_{sh}-value for special ductility RC structures can be evaluated using the minimum value between ρ_{sh1} ($=0.3\times(f'_c/f_{yh})\times[(A_g/A_{ch})-1]$) and ρ_{sh2} ($=0.09\times(f'_c/f_{yh})$).

Owing to lack of some necessary data, the compressive strength of concrete and concrete cover were assumed as 25 MPa and 0.02 m, respectively. As such, the required strengthening ratio of PSFRP can be identified by deducting the required ρ_{sh}-value with the existing ρ_{si}-value. This in turn provides the number of required PSFRP's layer of which the thickness was 0.12 mm for one single layer. To satisfy the minimum amount of required ρ_{sh} following DPT-2018 code, the demand of PSFRP confinement for seismic deficient columns became 3, 8 and 12 layers, as reported in Table 5. The demand of recycled PS to achieve seismic resistance can be estimated from the column areas (A_{column}), required PSFRP's layer (n_{PSFRP}), and the amount of PS per area (455 straws/m^2). Ultimately, a total of 43,133 straws can be recycled for producing PSFRP to seismically upgrade these deficient columns, increasing the use of PS wastes up to 30 times of the small-scale cylinder test. This ignites the future implementation of PSFRP in actual deficient columns in the earthquake-prone areas.

5. Conclusions

This study aimed for the first time to produce the plastic-straw fibre reinforced polymer (PSFRP) from the plastic-straw wastes for concrete confinement. The effects of PSFRP confinement on the compressive strength of concrete cylinders were investigated. The key parameter is the number of PSFRP's plies (1 to 3 plies) wrapped on both normal and low strength concrete specimens. The environmental impact assessment was conducted to ascertain the efficiency of the PSFRP. The conclusions could be demonstrated as follows:

1) As Covid-19 pandemic critically caused higher consumption of single-use plastics, it is important to reduce those wastes through recycling them as alternative construction materials. Producing FRP using plastic-straw wastes is possible with simple manufacturing process by local people. In engineering point of view, the mechanical properties of PSFRP such as tensile strength and ultimate tensile strain are satisfactory for strengthening purpose. However, the integrity between plastic-straw sheets and matrix is still an unsolved issue since surface of plastic straws is considered slippery, leading to delamination between PSFRP layer. This also indicates that the suitable epoxy resin as the matrix of PSFRP composites should properly applied on PS sheets for the future study.
2) Concerning strength enhancement due to PSFRP confinement, the compressive strength enhancement was increased the compressive strength of concrete in a range of 2.41% to 28.37%. The PSFRP confinement contributes a larger strengthening effect for low strength concrete with 3 plies of PSFRP. This may be because the effective confinement from 3-ply PSFRP jackets is higher than that of concrete with smaller amount of PSFRP plies. Comparing strength enhancement for concrete confined with PSFRP and JFRP, the increment strength of PSFRP is higher than that of JFRP when applying the same FRP volumetric ratio, indicating good performance of PSFRP.
3) Regarding environmental impact, PSFRP can significantly reduce amount of plastic-straw wastes. In this research, strengthening of a total of 24 concrete cylinders can eliminate the total of 1,440 plastic straws, indicating effective waste management by recycling plastic straws. As for the actual strengthening of reinforced concrete columns, it demands more strengthening areas than that in a small-scale concrete cylinder test, implying more demand of PS wastes. The existing seismic deficient columns of 4 school buildings were evaluated in terms of their level of insufficient transverse reinforcement as well as required PSFRP strengthening. As such, a total of 43,133 straws can be recycled for producing PSFRP to seismically retrofit these deficient columns, expanding the use of PS wastes up to 30 times of the small-scale cylinder test. Further implementation of PSFRP strengthening in actual full-scale concrete columns should be intensively performed to identify its applicability and evaluate the environmental impact.

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