sustainability

MDPI

Article

Utilization of Recycled Plastic Waste in Fiber Reinforced Concrete for Eco-Friendly Footpath and Pavement Applications

Cherdsak Suksiripattanapong [1,*], Taweerat Phetprapai [1], Witawat Singsang [2], Chayakrit Phetchuay [1], Jaksada Thumrongvut [1] and Wisitsak Tabyang [3,*]

[1] Department of Civil Engineering, Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima 30000, Thailand; taweerat.ph@rmuti.ac.th (T.P.); chayakrit.ph@rmuti.ac.th (C.P.); jaksada.th@rmuti.ac.th (J.T.)

[2] Department of Aircraft Part Manufacturing Technology, Faculty of Industrial Technology, Rambhai Barni Rajabhat University, Chanthaburi 22000, Thailand; wittawat.s@rbru.ac.th

[3] Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla 90000, Thailand

* Correspondence: cherdsak.su@rmuti.ac.th (C.S.); wisitsak.t@rmutsv.ac.th (W.T.)

Abstract: The use of concrete in road construction has grown over the past decade due to the material's great durability. However, concrete has poor tensile strength, ductility, and energy absorption. This paper aims to investigate the utilization of plastic waste, namely polypropylene (PP), to create a novel fiber to enhance the engineering properties of fiber reinforced concrete (FRC), an eco-friendly concrete that can reduce environmental problems. The 28-day design strengths of 28 and 32 MPa were used in this study because the compressive strength requirements for concrete footpaths and pavement specified by Austroads and the Department of Highways, Thailand, were at least 25 and 32 MPa, respectively. The fiber (F) was a mixture of virgin PP and recycled PP (RPP). The study used F contents of 0.25, 0.50, 0.75, and 1% by weight of cement and PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. The compressive strength, flexural strength, leaching, and CO_2 emissions savings of FRC were evaluated. Improvements in the compressive strength, flexural strength, and toughness of the samples with F were observed in comparison to the control concrete samples for all design strengths. All mixtures met the compressive strength requirements for concrete footpaths, except for F contents of 0.75 and 1% and a PP:RPP ratio of 0:100. By contrast, the 32 MPa FRC samples with F contents of 0.25 and 0.5% and all PP:RPP ratios met the requirements for rigid pavement. From an environmental perspective, the heavy metal contaminants of the 32 MPa FRC sample were within the allowable limits for all mixtures. Regarding incineration disposal, the maximum CO_2 emissions savings of 28 MPa and 32 MPa FRC with an F content of 0.5% and a PP:RPP ratio of 0:100 were 1.0 and 1.11 kg CO_2-e/m^3, respectively. This research will enable plastic waste, traditionally destined for incineration and landfill disposal, to be used as a sustainable fiber in the construction industry.

Keywords: plastic waste; recycled polypropylene fiber; heavy metals; CO_2 emissions savings

check for updates

Citation: Suksiripattanapong, C.; Phetprapai, T.; Singsang, W.; Phetchuay, C.; Thumrongvut, J.; Tabyang, W. Utilization of Recycled Plastic Waste in Fiber Reinforced Concrete for Eco-Friendly Footpath and Pavement Applications. *Sustainability* **2022**, *14*, 6839. https://doi.org/10.3390/su14116839

Academic Editor: José Ignacio Alvarez

Received: 11 May 2022
Accepted: 2 June 2022
Published: 2 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Infrastructure development plays an important role in stimulating a country's economic growth. Pavement, one component of infrastructure, includes both rigid and flexible pavement. Rigid pavement is constructed from cement concrete, which is widely used worldwide. The advantages of cement concrete pavement are its high strength and durability compared to flexible pavement. However, cement concrete pavement has poor flexural strength, ductility, and energy absorption. In addition, the use of cement concrete pavement results in large CO_2 emissions, adding to global warming [1]. As a result, the utilization of waste materials to enhance the properties of pavement materials is of interest to researchers. Their goal is to identify preferred strategies that are in accordance with sustainable development goals around the world [2].

Global annual solid waste generation amounts to approximately 2.01 billion tons and is forecasted to reach 3.40 billion tons by 2050 [3]. The United Nations (UN) Environment Programme reported in 2019 that the world generates over 300 million tons of plastic garbage each year. However, only 14% of that material is collected for recycling, and only 9% is actually recycled [4]. In 2018, Thailand produced 27.8 million tons of solid waste, of which 39% was correctly disposed of, 34% was recycled, and 27% was illegally disposed of (open dumping) [5]. Annually, 2.33 million tons of plastic are manufactured. Plastic consumption has grown by 7–8% every year, leading to waste management problems related to recycling, incineration, and disposal [6,7]. Incineration has the disadvantage of emitting large amounts of CO_2 into the environment and atmosphere. Furthermore, since plastic waste does not decay, corrode, or dissolve, it contributes to environmental contamination [8,9]. Thus, utilizing plastic waste to enhance the properties of concrete for concrete footpaths and pavement applications is environmentally advantageous.

Numerous studies in the concrete construction field have examined the utilization of plastic waste, including polyethylene terephthalate (PET) [10–13], polyethylene (PE) [14,15], and polypropylene (PP) [16–19]. The plastic waste that has been utilized in concrete includes aggregate and synthetic fibers [14,19–23]. Basha et al. [13] studied the mechanical characteristics of lightweight recycled plastic aggregate concrete and concluded that utilizing 100% and 25% recycled plastic aggregate provided unit weights of 1500 and 2000 kg/m^3 and compressive strengths of 17 and 35 MPa, respectively. Abu-Saleem et al. [19] investigated the strength of recycled plastic aggregate concrete using PET, High-Density PE, and PP. These recycled plastic types were treated with microwave radiation to improve the adhesion of the plastic particles to the matrix, resulting in an increase in concrete strength [20].

Additionally, reinforcing concrete with plastic fibers can improve several mechanical properties due to the effect of fiber bridging across the cracks [21–23]. At optimum fiber content, plastic fiber reinforced concrete indicated higher flexural strength and toughness than unreinforced concrete [24]. However, the high fiber content may decrease workability and increase porosity because of pore connectivity in the interfacial transition zone (ITZ) [25], resulting from the material's smooth surface and hydrophobic nature [26,27]. Sukontasukkul et al. [23] reported that the maximum compressive strength of high calcium fly ash geopolymer mortar was found at a PP fiber content of 0.5% by volume fraction. Similarly, Chindaprasirt et al. [24] concluded that 0.5% and 1.0% PP fiber contents by weight of FA offered the maximum compressive strength and flexural strength, respectively. Yin et al. [28] produced fiber from 50% virgin and 50% recycled polypropylene using a melt spinning and hot drawing method in an industrial factory. They found that a 50% virgin and 50% recycled PP fiber blend had the same tensile strength as, but a greater Young's modulus than, virgin PP fiber. The properties of recycled polypropylene fibers in concrete for footpath applications were studied by Yin et al. [29], who concluded that the energy absorption of fiber reinforced concrete with a virgin PP to recycled PP ratio of 50:50 was higher than that using only virgin PP fiber due to the greater Young's modulus and tensile strength. The lowest energy absorption was found when using recycled PP fiber [30,31].

Although research has been conducted on the use of plastic waste in concrete applications, an engineering and environmental evaluation of recycled plastic waste fiber reinforced concrete has not been done previously, and this is the focus of the current research. This paper aims to explore the utilization of plastic waste to create a novel fiber, which is a mixture of virgin polypropylene (PP) and recycled polypropylene (RPP), to improve the engineering properties of fiber reinforced concrete (FRC) for eco-friendly concrete footpaths and rigid pavement. The compressive and flexural strengths of FRC were investigated, along with its environmental impacts via a leaching test according to the toxicity characteristic leaching procedure (TCLP) and its CO_2 emissions savings. The influence factors studied were design strength, fiber content, and PP:RPP ratio. This research will enable plastic waste, which is currently intended for incineration and landfill disposal, to be utilized as a sustainable fiber in concrete footpaths and pavement.

2. Materials and Methods

2.1. Materials

The aggregate materials used in this study consisted of coarse and fine aggregates. The coarse aggregate was crushed limestone collected from a stone mill factory in Pak Chong District, Nakhon Ratchasima Province, Thailand. The maximum size, water absorption, and specific gravity of the coarse aggregate were 19 mm, 0.43%, and 2.70, respectively [32,33]. River sand with a specific gravity of 2.60 was used as the fine aggregate [34]. The maximum size and water absorption of the fine aggregate were 4.75 mm and 0.47%, respectively [32]. The particle size distribution of the aggregate materials is shown in Figure 1. The particle sizes of the aggregate material samples were prepared according to ASTM C33 [35].

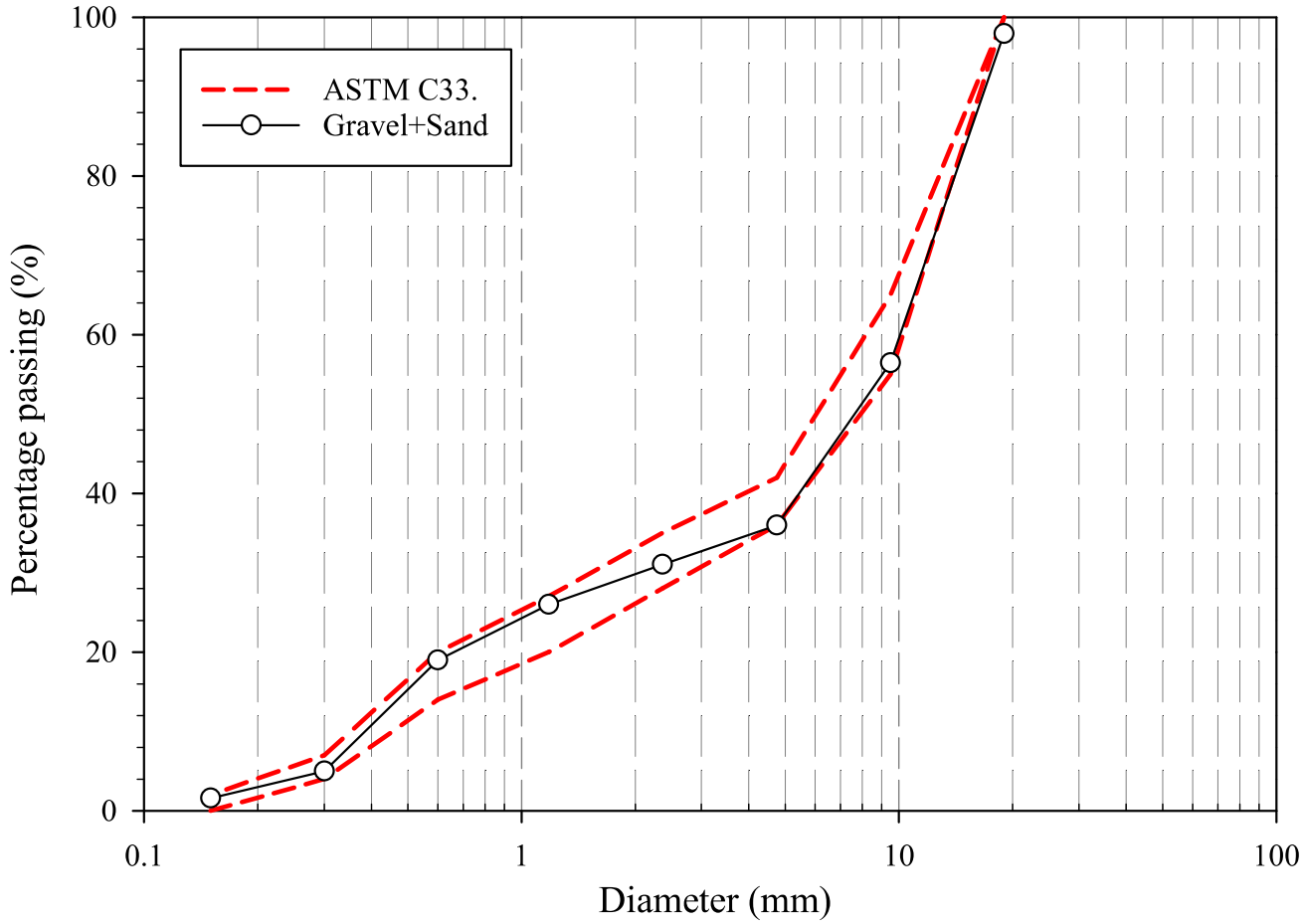


Figure 1. Grain size distribution curves of aggregate.

Ordinary Portland cement (OPC) was used in this study. The OPC had a specific gravity of 3.09, and its chemical properties are listed in Table 1. The main chemical in the OPC was calcium (CaO) at 66.53%. Silica (SiO_2) and alumina (Al_2O_3) made up 19.88 and 4.88% of the OPC, respectively.

The PP and RPP pellets were obtained from IRPC Public Co., Ltd. (Rayong, Thailand) and Thai Rung Rueang Plastic Co., Ltd. (Samut Prakan, Thailand), respectively, as shown in Figure 2a. In this study, the fibers at PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100 were mixed and extruded at a temperature of 315 °C and a stretching temperature of 140–170 °C. The fiber specimens at PP:RPP ratios of 100:0 and 0:100 are shown in Figure 2b,c, respectively. The density of the fibers was 0.90–0.95 g/cm^3. The fibers had a nominal diameter of 2 ± 0.1 mm. The fibers were cut into pieces 50 mm in length. The tensile properties of the plastics were evaluated according to ASTM D638-14 [36].

Table 1. Chemical composition of OPC.

Chemical Compositions	OPC (%)
SiO_2	19.88
Al_2O_3	4.88
Fe_2O_3	3.18
CaO	66.53
MgO	1.48
SO_3	2.91
K_2O	0.20
LOI	0.96



(**a**)



(**b**)



(**c**)

Figure 2. The appearance of (**a**) PP and RPP pellets, (**b**) PP fiber, and (**c**) RPP fiber.

2.2. Sample Preparation and Testing

The concrete mix design method following ACI 211.1-91 [37] was used to prepare the 28 MPa and 32 MPa control concrete without fiber, with slump values varying between 75 and 100 mm. The mixed proportions of the control concrete and fiber reinforced concrete (FRC) are indicated in Table 2. The fiber (F) contents were used in four different percentages: 0.25, 0.50, 0.75, and 1% by OPC weight. PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100 were used. To prepare the specimens, dry fine aggregates and OPC were mixed for 2 min to obtain a uniform mixture. Then the F was added and mixed for another 3 min to ensure the homogeneity of the mixture. Next, tap water was added to the mixture, and mixing continued for another 2 min. In the final step, the coarse aggregates were added into the mixer, and mixing continued for 3 min. The fresh FRC was carted in molds 100 mm in diameter and 200 mm in height for the compressive strength test and 100 × 100 × 400 mm for the flexural strength test. The samples were wrapped in a plastic sheet and cured at room temperature, that is, 27–30 °C. At a curing time of 28 days, the samples were evaluated using a compressive strength test according to ASTM C39 [38] and a flexural strength test according to ASTM C78 [39]. To ensure data consistency, three specimens were created for each mix proportion, resulting in a total of 252 specimens for the compressive strength and flexural strength tests.

Table 2. The mix proportions of control concrete and FRC.

Item	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Fiber Content (%wt)	Fiber Content (kg/m^3)
28 MPa control concrete	353.24	739.91	1007.98	210	0	0
28 MPa Concrete + 0.25% F	353.24	739.91	1007.98	210	0.25	0.88
28 MPa Concrete + 0.50% F	353.24	739.91	1007.98	210	0.50	1.77
28 MPa Concrete + 0.75% F	353.24	739.91	1007.98	210	0.75	2.65
28 MPa Concrete + 1.0% F	353.24	739.91	1007.98	210	1.00	3.53
32 MPa control concrete	390.77	708.73	1007.98	210	0	0
32 MPa Concrete + 0.25% F	390.77	708.73	1007.98	210	0.25	0.98
32 MPa Concrete + 0.50% F	390.77	708.73	1007.98	210	0.50	1.95
32 MPa Concrete + 0.75% F	390.77	708.73	1007.98	210	0.75	2.93
32 MPa Concrete + 1.0% F	390.77	708.73	1007.98	210	1.00	3.90

The toxicity characteristic leaching procedure (TCLP) test is the technique recommended by the United States Environmental Protection Agency [40]. The TCLP experiments were conducted on 28-day 32 MPa FRC at fiber contents of 0 and 0.75% and PP:RPP ratios of 100:0 and 0:100 for various heavy metals. For the leachate testing, the samples were crushed into 9.5 mm particles. Then an acetic acid solution was prepared to extract the sample. A solid to liquid ratio of 1:20 was used. The mixture was agitated in the extraction vessels using end-over-end rotations at 30 rpm for 18 h. After removing suspended particles from the leachate, it was filtered through a 0.45-m filter. Finally, inductively coupled plasma mass spectrometry (ICP-MS) was used to determine the metals contained in the leachate.

3. Results and Discussions

3.1. Mechanical Characteristics

Figure 3 indicates the relationships between stress and strain for F at PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. The stress value of F increased as the strain increased up to the maximum value and beyond, and the stress tended to drop for all PP:RPP ratios. The maximum stress value of F was found at a PP:RPP ratio of 100:0, whereas the minimum stress value of F was found at a PP:RPP ratio of 0:100. The stress values of F at PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100 were 354, 325, 290, 265, and 225 MPa at maximum strain values of 0.055, 0.045, 0.038, 0.03, and 0.028, respectively. Similar trends were also reported by Yin [28], who concluded that F prepared with a PP:RPP ratio of 100:0 exhibited a 33% higher tensile strength than F prepared with a PP:RPP ratio of 0:100. Moreover,

Yin et al. [30] showed that the tensile strength of F prepared with a PP:RPP ratio of 100:0 was up to 25% lower than that of the F mixed with a PP:RPP ratio of 0:100. This is due to the addition of RPP in the specimens led to a lower molecular weight and shorter molecular chains as a result of higher crystallinity and different crystal sizes [29,30].

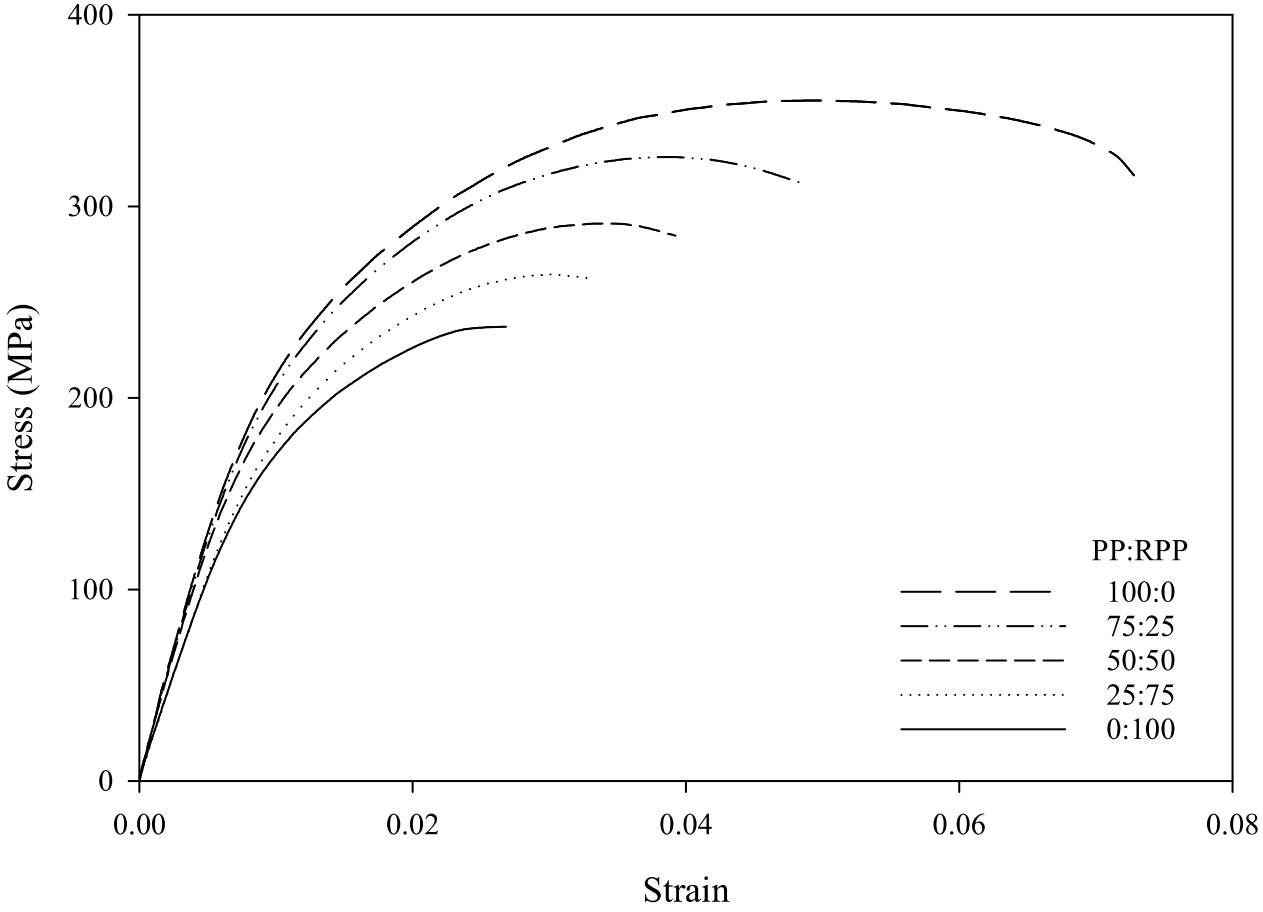
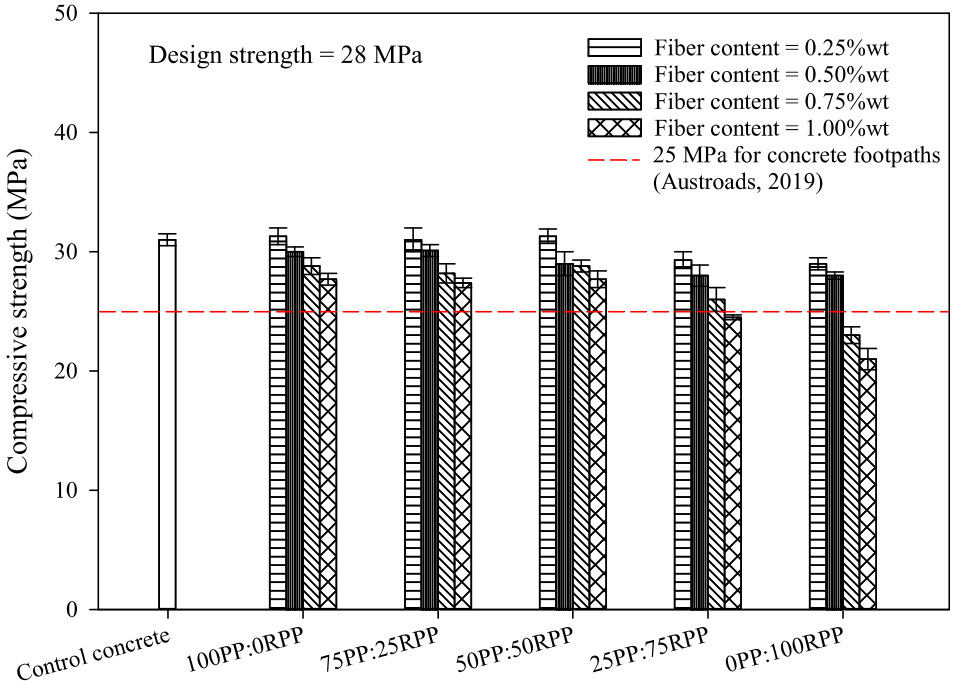
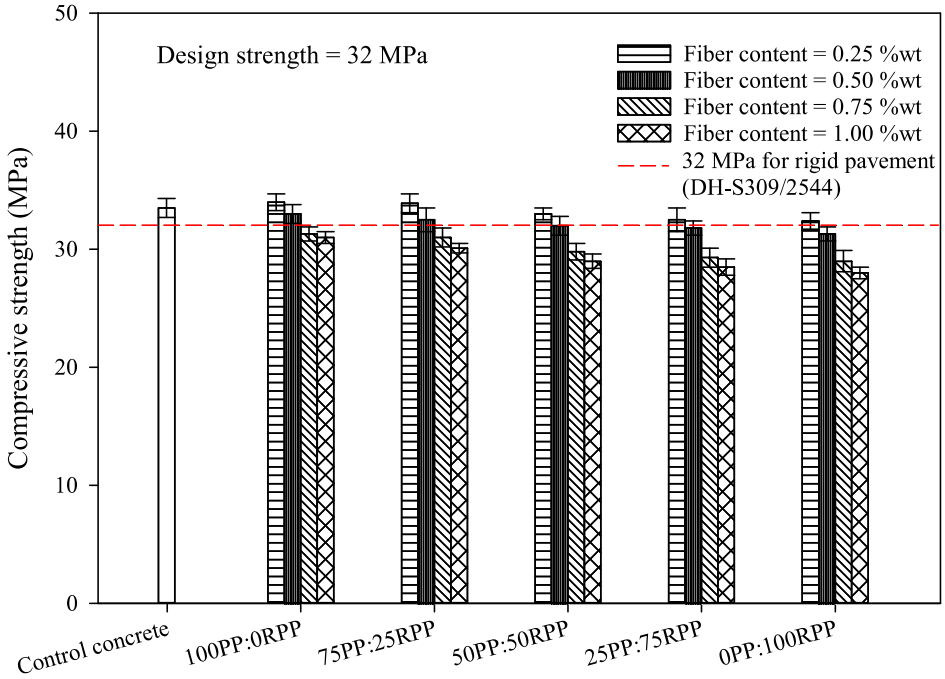


Figure 3. The relationship between stress and strain of F at different PP:RPP ratios.

The compressive strength requirements for concrete footpaths, as specified by Austroads [41], and for rigid pavement, as specified by the Department of Highways, Thailand [42], are at least 25 and 32 MPa, respectively. Therefore, design strength values of 28 and 32 MPa were used in this study. The compressive strengths of 28 and 32 MPa FRC at F contents of 0, 0.25, 0.50, 0.75, and 1% and PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100 are indicated in Figure 4. It can be noted that the 28-day design compressive strengths of 28 and 32 MPa control concrete were 31 and 33.5 MPa, respectively. The compressive strength of both the 28 and 32 MPa FRC increased with an F content of 0.25%, and when the F content was increased to 1% or greater, the compressive strength decreased for all PP:RPP ratios. For example, the compressive strength values of the 28 MPa FRC samples with a PP:RPP ratio of 100:0 were 31, 31.3, 29, 28.8, and 27.7 MPa for fiber contents of 0, 0.25, 0.50, 0.75, and 1%, respectively. The results are in good agreement with the results reported by Toghroli et al. [13], who concluded that incorporating 1 and 2% waste plastic fiber in the samples can increase compressive strength by 25 and 29%, respectively. This is because the sewing effect of fiber mitigates the stress concentration [13]. On the other hand, an excessive F content caused a large void in the sample, resulting from a lack of workability [7,43]. This finding agrees with the results reported by Sukontasukkul et al. [23]. In their study, the compressive strength of polypropylene fiber reinforced geopolymer decreased from 47 to 35 MPa for F contents of 0.5 and 1%, respectively.



(a)



(**b**)

Figure 4. Compressive strength of (**a**) 28 and (**b**) 32 MPa FRC at different F contents and PP:RPP ratios.

The effect of PP:RPP ratios on the compressive strength of 28 and 32 MPa FRC is shown in Figure 4. At a particular F content, the compressive strength of the 28 and 32 MPa FRC samples decreased for PP:RPP ratios ranging from 100:0 to 0:100. For example, the compressive strength values of the 32 MPa FRC sample with an F content of 0.25% were 34, 33.9, 33, 32.5, and 32.4 MPa for PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, respectively. A similar finding regarding a decrease in the compressive strength of FRC for PP:RPP ratios of 100:0 and 0:100 was also reported by Yin et al. [30]. In their study, the

compressive strength was found to decrease by about 4.4%. This is because the addition of RPP in the F results in decreased tensile strength and a decreased Young's modulus of F [29]. The maximum compressive strengths of 28 and 32 MPa FRC were found at a fiber content of 0.25% and a PP:RPP ratio of 100:0; these maximum compressive strengths values were 31.3 and 34 MPa, respectively. Considering the compressive strength requirements for concrete footpaths, all mixtures were suitable, except for those with F contents of 0.75 and 1% and a PP:RPP ratio of 0:100. By contrast, the 32 MPa FRC samples with F contents of 0.25 and 0.5% met the rigid pavement requirements for all PP:RPP ratios.

Figures 5 and 6 indicate the relationship between load and deflection for 28 and 32 MPa FRC. It can be seen that the load–deflection curves for 28 and 32 MPa FRC were higher than those for the control concrete for all fiber contents and PP:RPP ratios. This is because the addition of F content results in the bridging effect. Furthermore, the concentration of stress was reduced as a result of the sewing effect of fibers, which enables the FRC sample to sustain a higher load until total failure [12,13]. Overall, loads increased with deflection up to the peak loads for all F contents, PP:RPP ratios, and design strengths. Beyond the peak loads, 28 and 32 MPa FRC maintained the load, except for those samples with an F content of 0.25%. This is because an F content of 0.25% was insufficient to cause the fiber bridging effect and the sewing effect [12,13]. Therefore, the ductile behavior of 28 and 32 MPa FRC was found at F contents higher than 0.25%. On the other hand, 28 and 32 MPa FRC with a fiber content lower than 0.25% demonstrated brittle behavior.

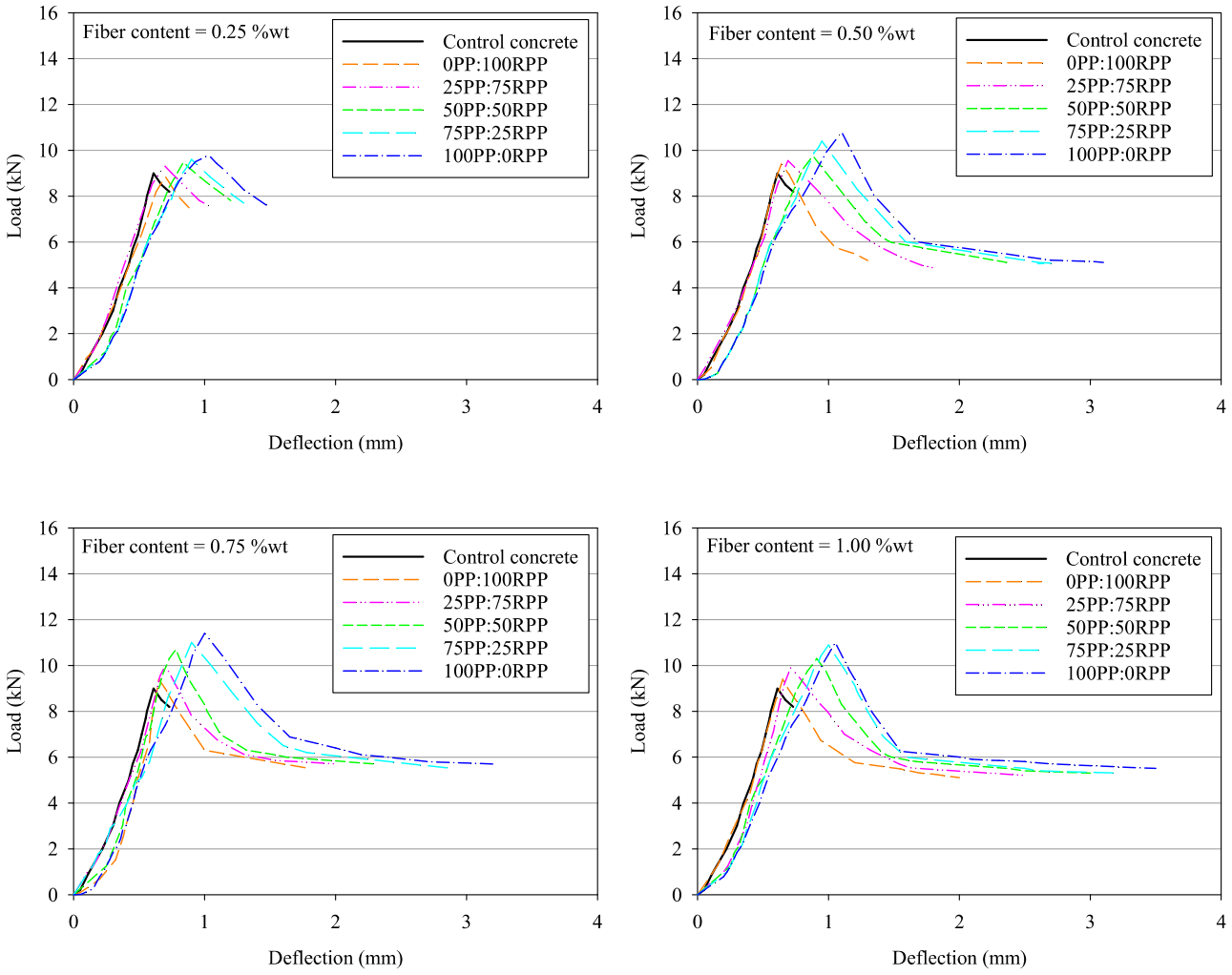


Figure 5. Relationship between load and deflection of 28 MPa FRC at different F contents and PP:RPP ratios.

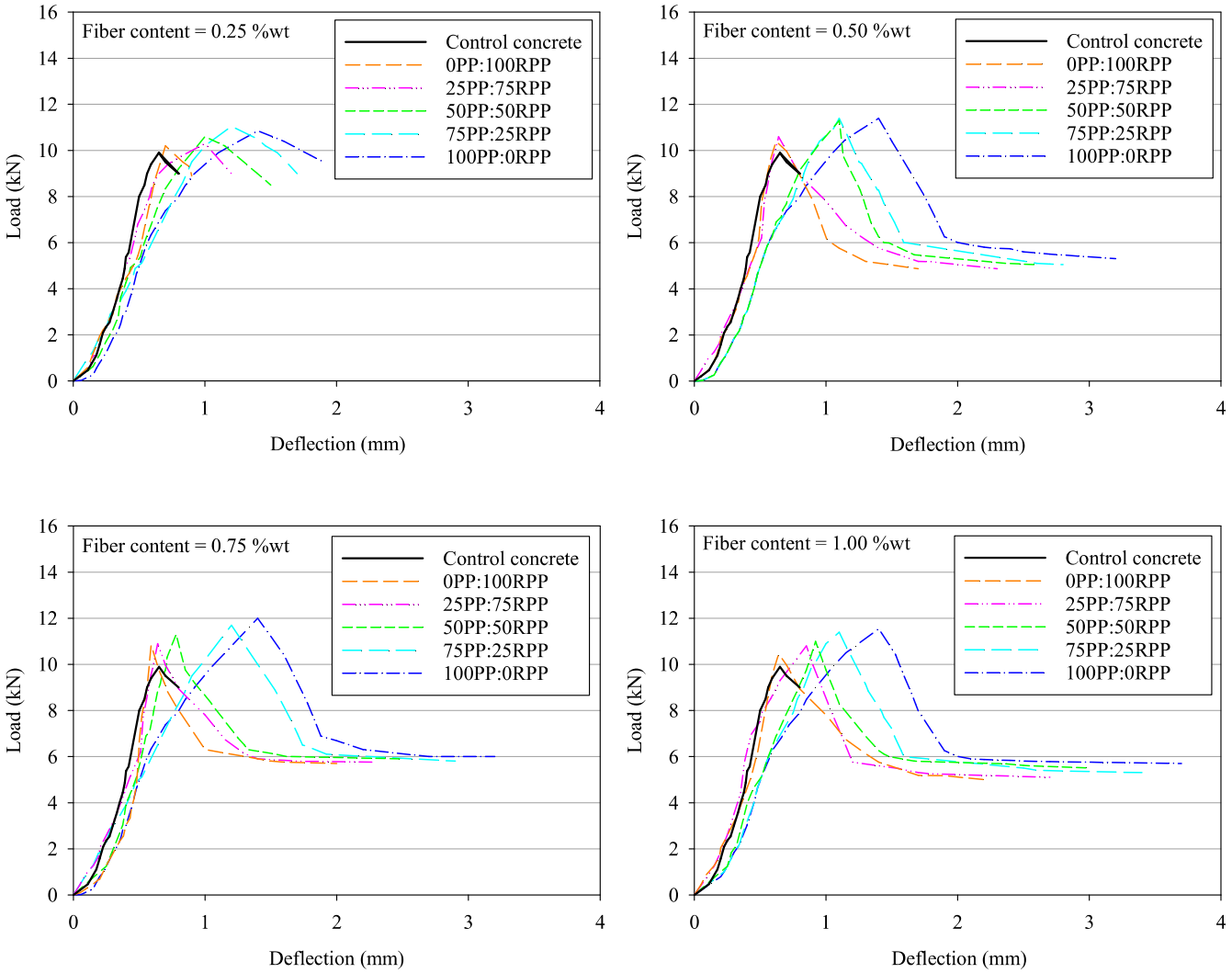


Figure 6. Relationship between load and deflection of 32 MPa FRC at different F contents and PP:RPP ratios.

Figure 7 shows the flexural strengths of 28 and 32 MPa FRC. It demonstrates that the flexural strength values of 28 and 32 MPa FRC were higher than those of the control concrete for all F contents and PP:RPP ratios. For example, the flexural strengths of the 32 MPa FRC samples with a PP:RPP ratio of 0:100 were 4.5, 4.69, 4.75, and 4.7 MPa for F contents of 0.25, 0.50, 0.75, and 1%, respectively, whereas the flexural strength of the control concrete was 4.4 MPa. This is because the fiber enhances the tensile strength of the sample [17,30].

The maximum flexural strength of both the 28 and 32 MPa FRC samples was found at an optimum fiber content of 0.75% for all PP:RPP ratios. For F contents lower than optimum, the flexural strength of the 28 and 32 MPa FRC samples increased as F content increased because of fiber bridging across the cracks [21–23]. Beyond the optimum fiber content, the flexural strength of the samples decreased due to less workability resulting in high porosity [24,27]. In addition, the smooth surface and hydrophobic nature of the material caused pore connectivity in the interfacial transition zone (ITZ) [25–27].

At a particular F content, the flexural strength of the 28 and 32 MPa FRC samples decreased with PP:RPP ratios ranging from 100:0 to 0:100 due to the reduced tensile strength of the fiber. This was associated with a decrease in compressive strength. The flexural strength requirements for rigid pavement specified by Austroads [41] and the Department of Highways, Thailand [42] were at least 4.5 and 4.2 MPa, respectively. All 32 MPa FRC

mixtures met Thailand's criterion [42], whereas the 32 MPa FRC samples with F contents of 0.25 and 0.5% at all PP:RPP ratios met the requirement specified by Austroads [41].

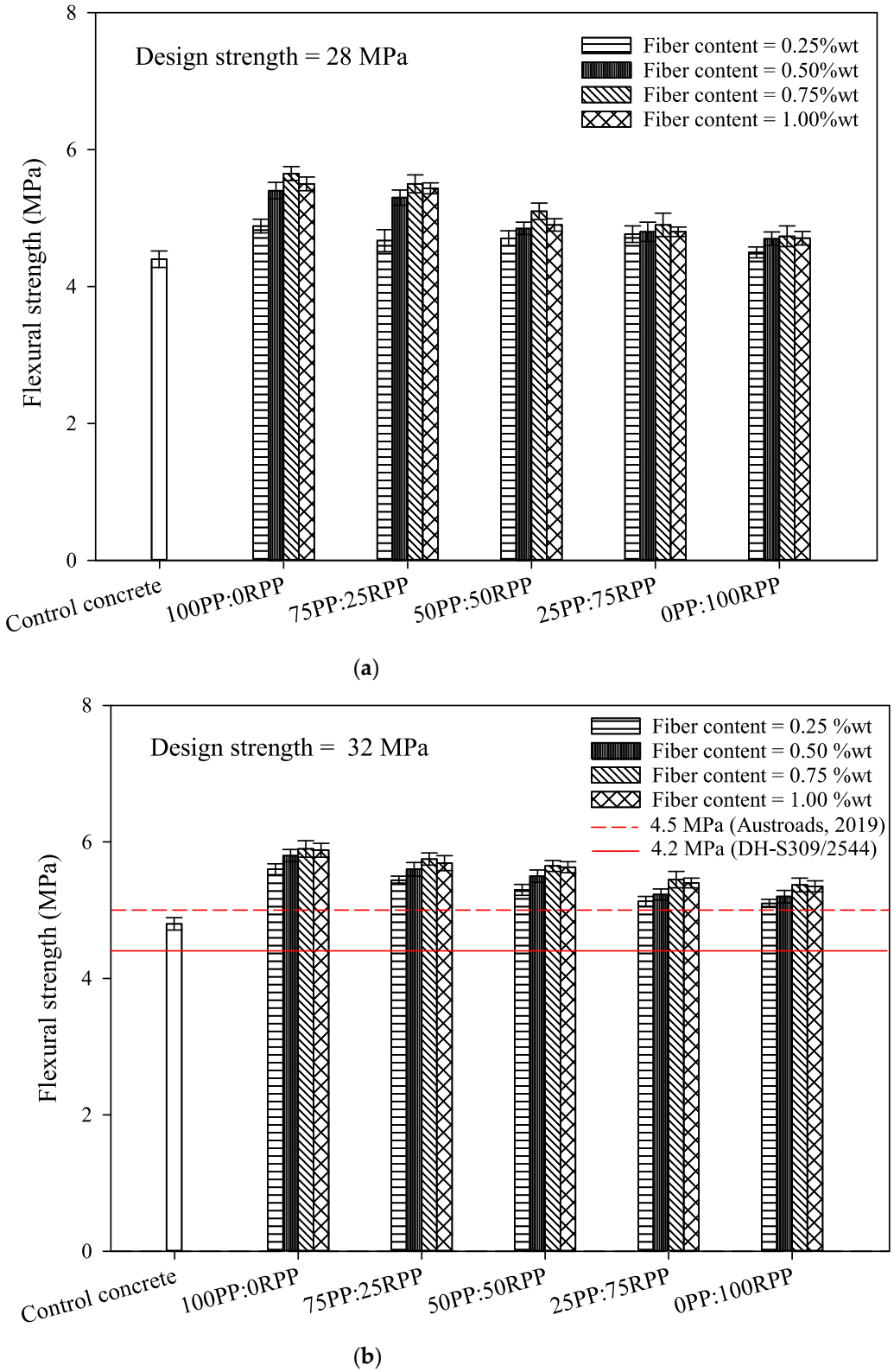
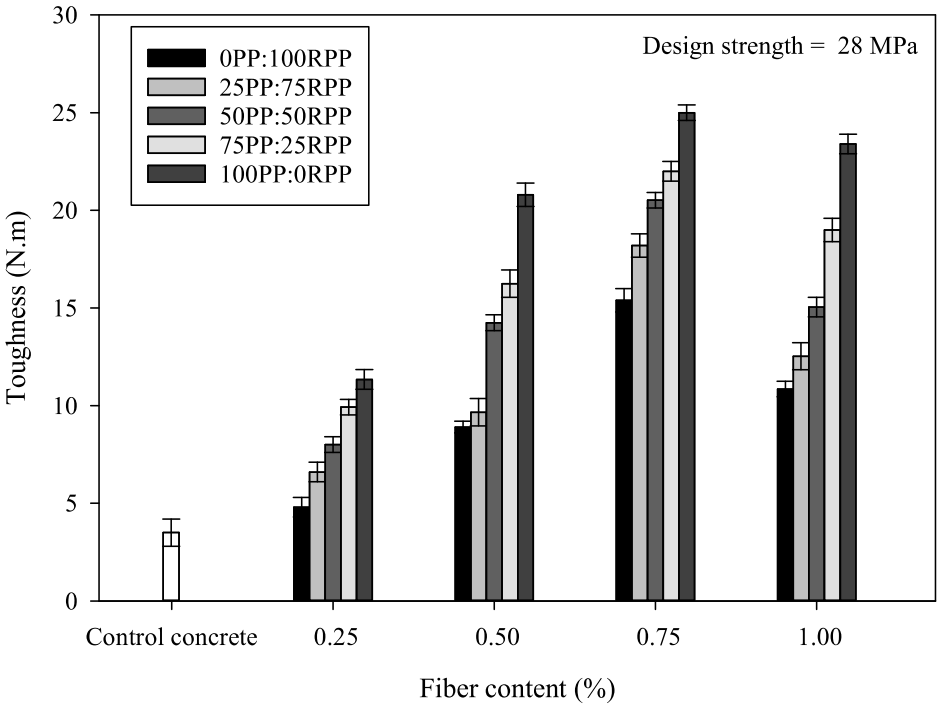


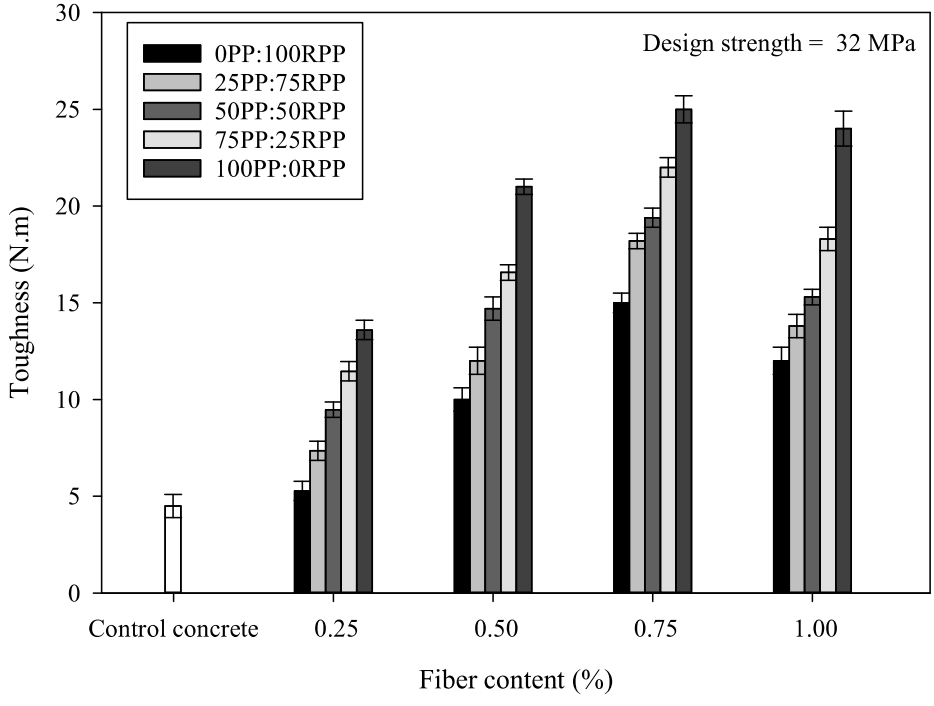
Figure 7. Flexural strength of (**a**) 28 and (**b**) 32 MPa FRC at different F contents and PP:RPP ratios.

The toughness values of 28 and 32 MPa FRC are shown in Figure 8. Following JSCE SF-4 [44], the area under the load–deflection curve up to L/150 was used to calculate the

toughness of the sample. The 28 and 32 MPa FRC samples with an F content of 0.75% and a PP:RPP ratio of 100:0 offered the maximum toughness due to the fiber bridging effect and the sewing effect [12,13]. The toughness of the samples decreased when the F content reached 1.0%, because a large void in the sample caused a reduction in the bonding between F and concrete [26].



(**a**)



(**b**)

Figure 8. Toughness of (**a**) 28 and (**b**) 32 MPa FRC at different F contents and PP:RPP ratios.

3.2. Environmental Impacts

In order to use recycled plastic waste fiber in concrete footpaths and rigid pavement, the environmental impacts in terms of the risks, hazards, and carbon footprint of using recycled polypropylene need to be evaluated. The heavy metal contaminant limits for drinking water defined by the U.S. Environmental Protection Agency [45] and the industrial waste hazard regulations specified by the Environmental Protection Agency of Victoria, Australia [46,47] were used in this study. Table 3 shows the leachate results for 32 MPa FRC at fiber content levels of 0 and 0.50% and PP:RPP ratios of 100:0 and 0:100. The highest heavy metal concentrations for 32 MPa FRC were found at an F content of 0.50% and a PP:RPP ratio of 0:100; these were 0.007, 0.002, 0.013, and 0.573 mg/L for arsenic, cadmium, chromium, and zinc, respectively. In contrast, the control concrete had the lowest heavy metal concentrations, at <0.001 and 0.009 mg/L for arsenic and chromium, respectively. However, the heavy metal contaminants in the 32 MPa FRC sample were within the allowable limits for all mixtures.

Table 3. Leachate results for FRC.

Contaminant	Control Concrete (mg/L)	Concrete with 100PP:0RPP Ratio (mg/L)	Concrete with 0PP:100RPP Ratio (mg/L)	Drinking Water Standard	Industrial Waste Standard
Arsenic	<0.001	0.004	0.007	0.05	0.35
Cadmium	BDL	0.001	0.002	2.0	35
Chromium	0.009	0.011	0.013	0.1	2.5
Copper	BDL	BDL	BDL	1.3	100
Lead	BDL	BDL	BDL	0.015	0.5
Mercury	BDL	BDL	BDL	0.002	0.05
Zinc	BDL	0.099	0.573	-	150

Generally, the disposal of plastic waste entails incineration and landfill disposal, processes which emit CO_2 into the atmosphere. Therefore, the use of recycled plastic waste in concrete footpaths and rigid pavement can eliminate these CO_2 emissions. In order to calculate the CO_2 emissions savings (kg CO_2-e/m^3) for 28 and 32 MPa FRC at an F content of 0.5% and PP:RPP ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, the functional unit, defined as the unit constant (kg CO_2-e/m^3), was evaluated in this study [48,49]. Incineration disposal produced CO_2 emissions of 0.569 kg CO_2-e/kg, while landfill disposal resulted in CO_2 emissions of 0.271 kg CO_2-e/kg [50–52]. Table 4 indicates the CO_2 emissions savings for 28 MPa and 32 MPa FRC at an F content of 0.5% and different PP:RPP ratios. Regarding incineration disposal, the maximum CO_2 emissions savings for 28 MPa and 32 MPa FRC at an F content of 0.5% and a PP:RPP ratio of 0:100 were 1.0 and 1.11 kg CO_2-e/m^3, respectively. As a result, using recycled PP fiber in concrete production instead of incinerating it or disposing of it in a landfill is an alternative approach that reduces its environmental impact [50–52].

Table 4. The CO_2 emission savings of 28 MPa and 32 MPa FRC at the fiber content of 0.5% and different PP:RPP ratios.

Item	PP:RPP Ratio				
	100:0	75:25	50:50	25:75	0:100
28 MPa Concrete + 0.50% F; Incineration	0	0.25	0.5	0.75	1.00
28 MPa Concrete + 0.50% F; Landfill disposal	0	0.12	0.24	0.36	0.48
32 MPa Concrete + 0.50% F; Incineration	0	0.28	0.56	0.83	1.11
32 MPa Concrete + 0.50% F; Landfill disposal	0	0.13	0.27	0.40	0.53

4. Conclusions

This research studied the possibility of using recycled plastic waste fiber to improve the properties of FRC for eco-friendly concrete footpaths and rigid pavement. The following conclusions can be drawn:

- Improvements in the compressive strength, flexural strength, and toughness of the samples with F were observed in comparison to the control concrete samples for design strengths of 28 and 32 MPa.
- The maximum compressive strengths of 28 and 32 MPa FRC, 31.3 and 34 MPa, respectively, were found at a fiber content of 0.25% and a PP:RPP ratio of 100:0, whereas, the maximum flexural strength and toughness of the 28 and 32 MPa FRC samples were found at an optimum F content of 0.75% for all PP:RPP ratios.
- All mixtures met the compressive strength requirements for concrete footpaths, except for those with F contents of 0.75 and 1% and a PP:RPP ratio of 0:100. Meanwhile, the 32 MPa FRC sample with F contents of 0.25 and 0.5% for all PP:RPP ratios met the minimum requirements for rigid pavement.
- The heavy metal contaminants in the 32 MPa FRC sample were within the allowable limits for all mixtures. The maximum CO_2 emissions savings of 28 MPa and 32 MPa FRC were found at a fiber content of 0.5% and a PP:RPP ratio of 0:100. Future research should focus on the effect of F content and PP:RPP ratio on the strength and permeability of fiber-reinforced pervious concrete.

Author Contributions: Conceptualization, C.S. and W.S.; methodology, T.P.; investigation, C.S., W.S. and T.P.; resources, C.S., W.T. and W.S.; writing—original draft preparation, C.S.; writing—review and editing, W.T., C.P., J.T. and W.T.; supervision, C.S.; project administration, C.S.; funding acquisition, C.S. and W.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research has received funding support from the NSRF via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant No. B05F640177.

Acknowledgments: The authors would like to acknowledge the support from Rajamangala University of Technology Isan and Rajamangala University of Technology Srivijaya.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Toghroli, A.; Shariati, M.; Sajedi, F.; Ibrahim, Z.; Koting, S.; Mohamad, E.T.; Khorami, M. A review on pavement porous concrete using recycled waste materials. *Smart Struct. Syst.* **2018**, *22*, 433–440.
2. Al-Kheetan, M.J.; Ghaffar, S.H.; Awad, S.; Chougan, M.; Byzyka, J.; Rahman, M.M. Microstructural, mechanical and physical assessment of Portland cement concrete pavement modified by sodium acetate under various curing conditions. *Infrastructures* **2021**, *6*, 113. [CrossRef]
3. Kaza, S.; Yao, L.; Bhada-Tata, P.; Woerden, F.V. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; World Bank Publications: Washington, DC, USA, 2018.
4. Silva, T.R.; Azevedo, A.R.G.; Cecchin, D.; Marvila, M.T.; Amran, M.; Fediuk, R.; Vatin, N.; Karelina, M.; Klyuev, S.; Szelag, M. Application of Plastic Wastes in Construction Materials: A Review Using the Concept of Life-Cycle Assessment in the Context of Recent Research for Future Perspectives. *Materials* **2021**, *14*, 3549. [CrossRef]
5. Marks, D.; Miller, M.A.; Vassanadumrongdee, S. The geopolitical economy of Thailand's marine plastic pollution crisis. *Asia Pac. Viewp.* **2020**, *61*, 266–282. [CrossRef]
6. Radusin, T.; Nilsen, J.; Larsen, S.; Annfinsen, S.; Waag, C.; Eikeland, M.S.; Petteren, M.K.; Fredriksen, S.B. Use of recycled materials as mid layer in three layered structures-new possibility in design for recycling. *J. Clean. Prod.* **2020**, *259*, 120876. [CrossRef]
7. Mohammadinia, A.; Wong, Y.C.; Arulrajah, A.; Horpibulsuk, S. Strength. Evaluation of utilizing recycled plastic waste and recycled crushed glass in concrete footpaths. *Constr. Build. Mater.* **2019**, *197*, 489–496. [CrossRef]
8. Siddique, R.; Khatib, J.; Kaur, I. Use of recycled plastic in concrete: A review. *Waste Manag.* **2008**, *28*, 1835–1852. [CrossRef]
9. Yazdani, M.; Kabirifar, K.; Frimpong, B.E.; Shariati, M.; Mirmozaffari, M.; Boskabadi, A. Improving construction and demolition waste collection service in an urban area using a simheuristic approach: A case study in Sydney, Australia. *J. Clean. Prod.* **2021**, *280*, 124138. [CrossRef]
10. Awoyera, P.O.; Adesina, A. Plastic wastes to construction products: Status, limitations and future perspective. *Case Stud. Constr. Mater.* **2020**, *12*, e00330. [CrossRef]

11. Faraj, R.H.; Ali, H.F.H.; Sherwani, A.F.H.; Hassan, B.R.; Karim, H. Use of recycled plastic in self-compacting concrete: A comprehensive review on fresh and mechanical properties. *J. Build. Eng.* **2020**, *30*, 101283. [CrossRef]
12. Mehrabi, P.; Shariati, M.; Kabirifar, K.; Jarrah, M.; Rasekh, H.; Trung, N.T.; Jahandari, S. Effect of pumice powder and nano-clay on the strength and permeability of fiber-reinforced pervious concrete incorporating recycled concrete aggregate. *Constr. Build. Mater.* **2021**, *287*, 122652. [CrossRef]
13. Toghroli, A.; Mehrabi, P.; Shariati, M.; Trung, N.T.; Jahandari, S.; Rasekh, H. Evaluating the use of recycled concrete aggregate and pozzolanic additives in fiber-reinforced pervious concrete with industrial and recycled fibers. *Constr. Build. Mater.* **2020**, *252*, 118997. [CrossRef]
14. Basha, S.I.; Ali, M.R.; Al-Dulaijan, S.U.; Maslehuddin, M. Mechanical and thermal properties of lightweight recycled plastic aggregate concrete. *J. Build. Eng.* **2020**, *32*, 101710. [CrossRef]
15. Merli, R.; Preziosi, M.; Acampora, A.; Lucchetti, M.C.; Petrucci, E. Recycled Fibers in Reinforced Concrete: A systematic literature review. *J. Clean. Prod.* **2019**, *248*, 119207. [CrossRef]
16. Małek, M.; Jackowski, M.; Łasica, W.; Kadela, M. Characteristics of Recycled Polypropylene Fibers as an Addition to Concrete Fabrication Based on Portland Cement. *Materials* **2020**, *13*, 1827. [CrossRef] [PubMed]
17. Francioso, V.; Moro, C.; Castillo, A.; Velay-Lizancos, M. Effect of elevated temperature on flexural behavior and fibers-matrix bonding of recycled PP fiber-reinforced cementitious composite. *Constr. Build. Mater.* **2021**, *269*, 121243. [CrossRef]
18. Bhogayata, A.C.; Arora, N.K. Impact strength, permeability and chemical resistance of concrete reinforced with metalized plastic waste fibers. *Constr. Build. Mater.* **2018**, *161*, 254–266. [CrossRef]
19. Abu-Saleem, M.; Zhuge, Y.; Hassanli, R.; Ellis, M.; Rahman, M.M.; Levett, P. Microwave radiation treatment to improve the strength of recycled plastic aggregate concrete. *Case Stud. Constr. Mater.* **2021**, *15*, e00728. [CrossRef]
20. Abd-Elaal, E.; Al-Bataineh, S.A.; Mills, J.; Whittle, J.; Zhuge, Y. *Enhancing Mechanical Properties of Rubberised Concrete with Non-thermal Plasma Treatment. ACMSM25*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 23–32.
21. Sukontasukkul, P.; Chindaprasirt, P.; Pongsopha, P.; Phoo-Ngernkham, T.; Tangchirapat, W.; Banthia, N. Effect of fly ash/silica fume ratio and curing condition on mechanical properties of fiber-reinforced geopolymer. *J. Sustain. Cem.-Based Mater.* **2020**, *9*, 218–232. [CrossRef]
22. Sukontasukkul, P.; Jamnam, S.; Sappakittipakorn, M.; Fujikake, K.; Chindaprasirt, P. Residual flexural behavior of fiber reinforced concrete after heating. *Mater. Struct.* **2018**, *51*, 98. [CrossRef]
23. Sukontasukkul, P.; Pongsopha, P.; Chindaprasirt, P.; Songpiriyakij, S. Flexural performance and toughness of hybrid steel and polypropylene fibre reinforced geopolymer. *Constr. Build. Mater.* **2018**, *161*, 37–44. [CrossRef]
24. Chindaprasirt, P.; Boonbamrung, T.; Poolsong, A.; Kroehong, W. Effect of elevated temperature on polypropylene fiber reinforced alkali-activated high calcium fly ash paste. *Case Stud. Constr. Mater.* **2021**, *15*, e00554. [CrossRef]
25. Khoury, G.A. Polypropylene fibres in heated concrete. Part 2: Pressure relief mechanisms and modelling criteria. *Mag. Concr. Res.* **2008**, *60*, 189–204. [CrossRef]
26. López-Buendía, A.M.; Romero-Sánchez, M.D.; Climent, V.; Guillem, C. Surface treated polypropylene (PP) fibres for reinforced concrete. *Cem. Concr. Res.* **2013**, *54*, 29–35. [CrossRef]
27. Yoosuk, P.; Suksiripattanapong, C.; Sukontasukkul, P.; Chindaprasirt, P. Properties of polypropylene fiber reinforced cellular lightweight high calcium fly ash geopolymer Mortar. *Case Stud. Constr. Mater.* **2021**, *15*, e00730. [CrossRef]
28. Yin, S.; Tuladhar, R.; Shanks, R.A.; Collister, T.; Combe, M.; Jacob, M.; Tian, M.; Sivakugan, N. Fiber preparation and mechanical properties of recycled polypropylene for reinforcing concrete. *J. Appl. Polym. Sci.* **2015**, *132*, 41866. [CrossRef]
29. Yin, S.; Tuladhar, R.; Collister, T.; Combe, M.; Sivakugan, N.; Deng, Z. Post-cracking performance of recycled polypropylene fibre in concrete. *Constr. Build. Mater.* **2015**, *101*, 1069–1077. [CrossRef]
30. Yin, S.; Tuladhar, R.; Riella, J.; Chung, D.; Collister, T.; Combe, M.; Sivakugan, N. Comparative evaluation of virgin and recycled polypropylene fibre reinforced concrete. *Constr. Build. Mater.* **2016**, *114*, 134–141. [CrossRef]
31. Yin, S.; Tuladhar, R.; Sheehan, M.; Combe, M.; Collister, T. A life cycle assessment of recycled polypropylene fibre in concrete footpaths. *J. Clean. Prod.* **2016**, *112*, 2231–2242. [CrossRef]
32. *ASTM C127-15*; Standard Test Method for Relative Density (Specific Gravity) And Absorption of Coarse Aggregate. American Society for Testing and Materials: West Conshohocken, PA, USA, 2015.
33. *ASTM C136-14*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. American Society for Testing and Materials: West Conshohocken, PA, USA, 2014.
34. *ASTM C128-15*; Standard Test Method for Relative Density (Specific Gravity) And Absorption of Fine Aggregate. American Society for Testing and Materials: West Conshohocken, PA, USA, 2015.
35. *ASTM C33-16*; Standard Specification for Concrete Aggregates. American Society for Testing and Materials: West Conshohocken, PA, USA, 2016.
36. *ASTM D638-14*; Standard Test Method for Tensile Properties of Plastics. American Society for Testing and Materials: West Conshohocken, PA, USA, 2014.
37. *ACI PRC-211.1-91*; Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2009; pp. 1–38.
38. *ASTM C39-16*; Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. American Society for Testing and Materials: West Conshohocken, PA, USA, 2016.

39. *ASTM C78M-18*; Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). American Society for Testing and Materials: West Conshohocken, PA, USA, 2018.
40. United State EPA. *Toxicity Characteristic Leaching Procedure (TCLP)*; SW-846, Appendix II-Method 1311; U.S. Environmental Protection Agency: Washington, DC, USA, 1992.
41. Austroads. *Guide to Pavement Technology Part 2: Pavement Structural Design*; Austroads: Sydney, Australia, 2019.
42. *DH-S309/2544*; Standards for Highway Construction. Department of Highways: Bangkok, Thailand, 1996.
43. Tabyang, W.; Suksiripattanapong, C.; Wonglakorn, N.; Laksanakit, C.; Chusilp, N. Utilization of municipal solid waste incineration fly ash for non-bearing masonry units containing coconut fiber. *J. Nat. Fibers* **2022**. [CrossRef]
44. *JSCE SF-4*; Method of Test for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete. Japan Society of Civil Engineering: Tokyo, Japan, 1983; pp. 58–66.
45. EPA. *National Primary Drinking Water Standards*; Environment Protection Agency: Washington, DC, USA, 1999.
46. EPA. *Soil Hazard Categorisation and Management, Industrial Waste Resource Guidelines*; Publication No. IWRG 621; Environmental Protection Agency of Victoria: Carlton, Australia, 2009.
47. EPA. *Solid Industrial Waste Hazard Categorization and Management, Industrial Waste Resource Guidelines*; Publication No. IWRG 631; Environmental Protection Agency of Victoria: Carlton, Australia, 2009.
48. Tabyang, W.; Suksiripattanapong, C.; Phetchuay, C.; Laksanakit, C.; Chusilp, N. Evaluation of municipal solid waste incineration fly ash based geopolymer for stabilised recycled concrete aggregate as road material. *Road Mater. Pavement Des.* **2021**. [CrossRef]
49. Suksiripattanapong, C.; Sakdinakorn, R.; Tiyasangthong, S.; Wonglakorn, N.; Phetchuay, C.; Tabyang, W. Properties of soft Bangkok clay stabilized with cement and fly ash geopolymer for deep mixing application. *Case Stud. Constr. Mater.* **2022**, *16*, e01081. [CrossRef]
50. Suksiripattanapong, C.; Uraikhot, K.; Tiyasangthong, S.; Wonglakorn, N.; Tabyang, W.; Jomnonkwao, S.; Phetchuay, C. Performance of asphalt concrete pavement reinforced with high-density polyethylene plastic waste. *Infrastructures* **2022**, *7*, 72. [CrossRef]
51. Eriksson, O.; Finnveden, G. Plastic waste as a fuel—CO_2-neutral or not? *Energy Environ. Scr.* **2009**, *2*, 907–914. [CrossRef]
52. Turner, D.A.; Williams, I.D. Greenhouse gas emission factors for recycling of source-segregated waste materials. *Resour. Conserv. Recycl.* **2015**, *105*, 186–197. [CrossRef]