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An Experimental Study on Mechanical Behaviors of Carbon Fiber and Microwave-Assisted Pyrolysis Recycled Carbon Fiber-Reinforced Concrete

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Abstract: In the last decade, waste carbon fiber-reinforced plastic (CFRP) products have not been properly recycled and reused, and they sometimes cause environmental problems. In this paper, the microwave-assisted pyrolysis (MAP) technology was utilized to remove the resin from the CFRP bicycle frame, which was recycled into carbon fiber. A scanning electron microscope (SEM) and single filament tensile test were used to observe and compare the difference between recycled carbon fiber and normal carbon fiber. The mechanical performances of carbon fiber-reinforced concrete (CFRC) were investigated with static and dynamic tests under three different fiber/cement weight proportions (5‰, 10‰, and 15‰). Three different kinds of carbon fiber were used in this study, normal carbon fiber, carbon fiber without coupling agent, and recycled carbon fiber. The experimental program was tested according to ASTM C39-01, ASTM C293, and ACI 544.2R standards for compression, flexural, and impact test, respectively. From the experimental results, addition of 10‰ of carbon fiber into the concrete exhibited maximum compressive and flexural strength. The impact performance of recycled carbon fiber improved the highest impact number compared with normal carbon fiber under different impact energy.

Keywords: recycled carbon fiber; fiber-reinforced concrete; microwave-assisted pyrolysis; shock wave

1. Introduction

1.1. Background

Reinforced concrete structures are deteriorated by seismic and other loadings, which cause structural damage or failure. Recently, carbon fiber-reinforced plastics (CFRPs) have been widely used in structural repair and seismic retrofit. The merits of carbon fiber are that it does not corrode, degrade, fatigue, and it possesses high specific strength. In addition, CFRP is a composite material with carbon fiber as the stiffener and thermosetting or thermoplastic resins as the matrix. Therefore, it has been widely used in the aerospace industry, automotive industry, sports equipment, and civil engineering. However, CFRP is a kind of material that is difficult to decompose by nature and sometimes can produce toxic gases when burned. The traditional disposal of the waste CFRPs is harmful to the environment; thus, an effective recycling method is urgently needed to turn waste CFRPs into potential recycling products, such as the fiber of fiber-reinforced concrete used in civil engineering infrastructures. The world's population is increasing gradually, and it is affecting the environment by raw material wastage.

In the linear economy, renewable and nonrenewable raw material sources are collected and transformed into products until it is discarded as waste. For example, the CFRP bicycle frame has been used in linear economic material and it is discarded as waste. Recently, some carbon fiber composite material has been recycled in different methods, such as mechanical, thermal, and chemical recycling approaches. In this paper, microwave-assisted pyrolysis (MAP) technology approaches are used to remove the resin from the CFRP bicycle frame and transform it into recycled carbon fiber, and then it is used in fiber-reinforced concrete (FRC) structures; the waste materials have been recycled and turn the linear economy to a circular economy. The recycled carbon fiber from the CFRP wastes reduces environmental pollution by being applied in civil engineering.

1.2. Literature Review

Fiber-reinforced cement matrix materials can significantly improve the mechanical properties of fiber-reinforced cement or fiber-reinforced concrete. So far, there have been many studies on fiber-reinforced cement-based materials. Fiber-reinforced concrete can inhibit the formation of large cracks, control the development direction of concrete cracks, and improve the toughness of concrete, thereby improving the tensile and crack resistance of traditional concrete [1,2].

Compared with glass fiber and polypropylene (PP) fiber, steel fiber has better elastic modulus and tensile strength, and the steel fiber-reinforced concrete enhances the effect of shock absorption, compressive and flexural strength of concrete specimens. According to some research test results, adding silica fume can effectively disperse the steel fiber more evenly [3,4]; and adding 1.5% fiber proportion of steel fiber to concrete can increase the impact number in the free-fall impact test [4,5].

There have been many studies on the application of chopped carbon fiber in cement matrix materials over the last few decades. For example, the mechanical properties and microstructures of cement and concrete have been studied by using different types of carbon fibers, carbon fiber lengths, and carbon fiber proportion [6–13]. Furthermore, the level of dispersion of carbon fiber in the cement will greatly affect the strength of the specimen after solidification. Research has shown that different mixing methods will affect the level of dispersion of carbon fiber [14–17]. The carbon fibers were immersed in the hydrolysis method and the furnace heating method to remove silane on the surface of the carbon fiber. The furnace heating method can effectively remove the silane on the surface of the carbon fiber, and combining the furnace heating method with the pneumatic dispersion method can improve the chopped carbon fiber to uniformly disperse inside cement [18].

The amount of industrial waste and commercial waste increases with an increase in demand. Many scholars have begun to study the application of waste in civil engineering to improve the mechanical properties or durability of concrete. Polyethylene terephthalate (PET) waste replacement weight percentage and volume fraction affect the compressive strength. Due to the incorporation of PET waste, the flexural strength and split tensile strength were also deteriorating to the concrete, but the impact resistance had a tiny enhancement effect by weight percentage replacement with aggregates [19,20]. The addition of 1% volume fraction of metalized plastic waste (MPW) fibers into the concrete enhances the compressive strength and impact resistance [21]. The compressive strength was increased by using scrap tire fibers compared with scrap tire fragments. In addition, the fiber-reinforced concrete with a 0.8% weight proportion of recycled tire steel fiber (RTSF) and 0.2% of polypropylene fiber (PPF) had the highest compressive strength. Using PPF instead of RTSF will not greatly affect the flexural strength [22,23]. The glass fiber-reinforced plastics (GFRP) sheets were chopped into short fiber and incorporated into concrete. The recycled GFRP was not affected by alkaline aggregate reaction and shrinkage of concrete. The test results showed that 3 wt % aggregates replacement with GFRP attained maximum compressive and flexural strength. Adding recycled GFRP into concrete improves the impact strength of concrete, but it will reduce the slump flow [24–26]. The chopped recycled CFRP improves the compressive, flexural, and impact strengths of concrete [27–29]. Adding 3 wt % of CFRP waste into the mortar enhances the stiffness and also the flexural strength [29].

Based on the above research background and literature review, this research will use recycled carbon fiber obtained by microwave-assisted pyrolysis (MAP) technology and apply it to fiber-reinforced concrete. The three different types of carbon fibers (recycled carbon fiber, normal carbon fiber, and carbon fiber without coupling agent) were used with different fiber weight proportions (5‰, 10‰, and 15‰). Additionally, the pneumatic dispersion process was used to disperse the fibers uniformly into cement. The mechanical properties of recycled carbon fiber-reinforced concrete were studied through a compression test, three-point bending test, and impact test.

2. Materials

In this study, the mechanical behavior of concrete was enhanced by adding three types of chopped carbon fibers (normal carbon fiber, carbon fiber without coupling agent, and recycled carbon fiber). This section introduces the materials used in the preparation of CFRC, which include the material characteristics of carbon fiber, carbon fiber recycling technology, and coupling agent removal process.

2.1. Carbon Fiber

The lightweight polyacrylonitrile (PAN-based) carbon fibers, which have a high tensile and specific strength, have been applied to the aerospace industry, wind turbine, sports equipment, and automotive parts. The carbon fiber was obtained from Tairylan Division, Formosa Plastics Group; then, the fiber was chopped at Sheng Peng Applied Materials Co., Ltd. [30]. The material properties are listed in Table 1 [31].

Table 1. Material properties of chopped normal carbon fiber.

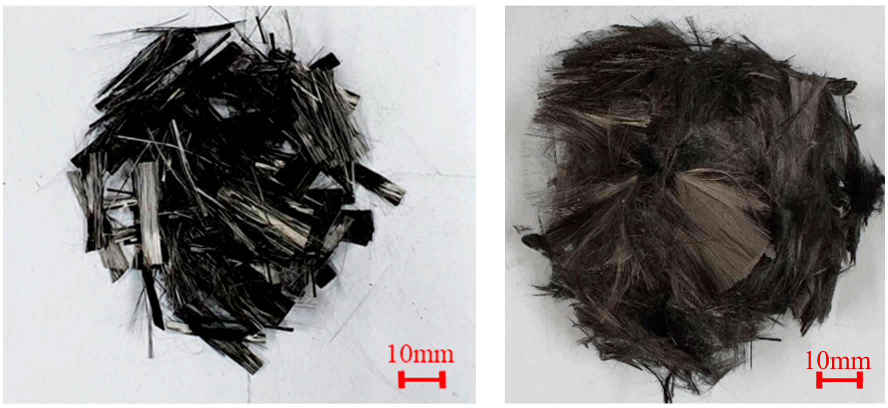
Material Property	Value
Tensile strength (MPa)	4900
Tensile modulus (GPa)	250
Elongation (%)	2.0
Density (g/cm^3)	1.81
Fiber diameter (μ)	7

2.2. Removal of Coupling Agent on the Surface of Carbon Fiber

The carbon fibers were immersed in pure water for one day, and then we performed GC-MS testing on the immersion solution to identify the type and boiling range of the coupling agent and other substances. The coupling agent was found to be $C_{26}H_{48}O_3Si$ with a molecular weight of 436.74 g/mol under the boiling point of 507.1 $\pm$ 50.0 °C at a pressure of 760 mm-Hg [18]. The removal of the coupling agent process is shown in Figure 1; the carbon fibers were wrapped with aluminum foil and then placed into a Muffle furnace (PF-40, Chuan-Hua Precision, New Taipei City, Taiwan) at a high temperature of 550 °C for 3 h.

Figure 1. Coupling agent removal processes. 1. Carbon fibers were wrapped with aluminum foil; 2. Placed the carbon fibers with aluminum foil into a Muffle furnace; 3. Set the furnace temperature at 550 °C for 3 h.

Generally, the coupling agent is an inorganic compound, and it reduces the adhesion between the fiber and cement. The differentiation of the coupling agent presence and absence on the surface of carbon fiber is shown in Figure 2. The carbon fiber is easier to distribute in the concrete by removing the coupling agent, compared with normal carbon fiber.



(**a**) (**b**)

Figure 2. The appearance of chopped carbon fiber: (**a**) Normal carbon fiber, (**b**) Carbon fiber without coupling agent.

2.3. Recycled Carbon Fiber

Carbon fiber tow is the thread used to weave carbon fiber fabrics. As a standalone product, it can be used to make wound parts, in pultrusion, or chopped as a local reinforcement. This 12 k tow (or yarn) comprises 12,000 individual carbon filaments, which boast the highest ultimate tensile strength in the industry. The microwave-assisted pyrolysis (MAP) is different from the traditional heating method. It uses microwaves to quickly rub the molecules in the substance, prompting the molecules to rotate quickly to generate heat, and then quickly decompose. The characteristics of microwave heating are: Microwaves only aim at the materials that can absorb them, so energy use is more concentrated. The electric power system is used to generate microwaves, it can be quickly heated, the process is easy to control, and automatic control can be realized. Microwaves penetrate to the absorbable substances, so they can heat the entire object uniformly [32,33].

In the MAP technology, the microwave heat radiations can transfer through the carbon fiber from inner to outer. It can remove the resin from the CFRP bicycle frame scrap to transfer into recycled carbon fiber. Figure 3 shows the microwave machine (PYRO 260, Milestone, Sorisole, Italy) at the Department of Molecular Science and Engineering Laboratory of the National Taipei University of Technology, Taipei, Taiwan. The recycled carbon fiber was obtained from the carbon fiber scrap by using the MAP process in the microwave machine at 950 °C for 1 h, and then a single filament tensile test was carried out.

Figure 3. The microwave machine.

In this study, both carbon fiber and recycled carbon fiber groups were tested in the single filament tensile test and carried out in accordance with ASTM D3379 [34]. Each group of carbon fibers had 30 individual filaments. The load–displacement relationships of the normal and recycled carbon fibers are shown in Figure 4.

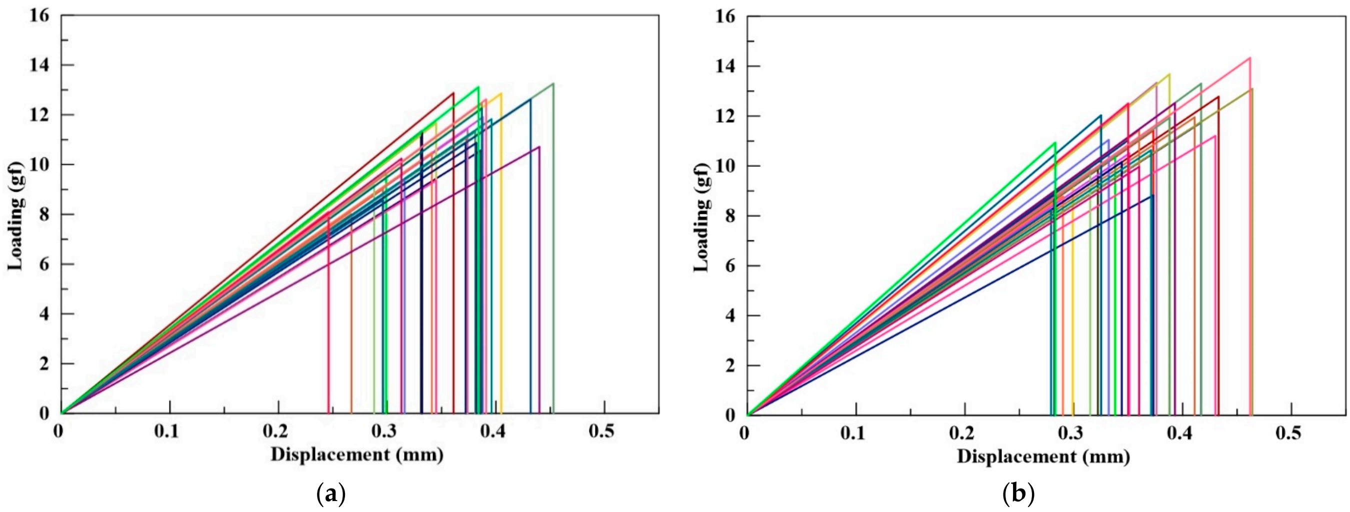
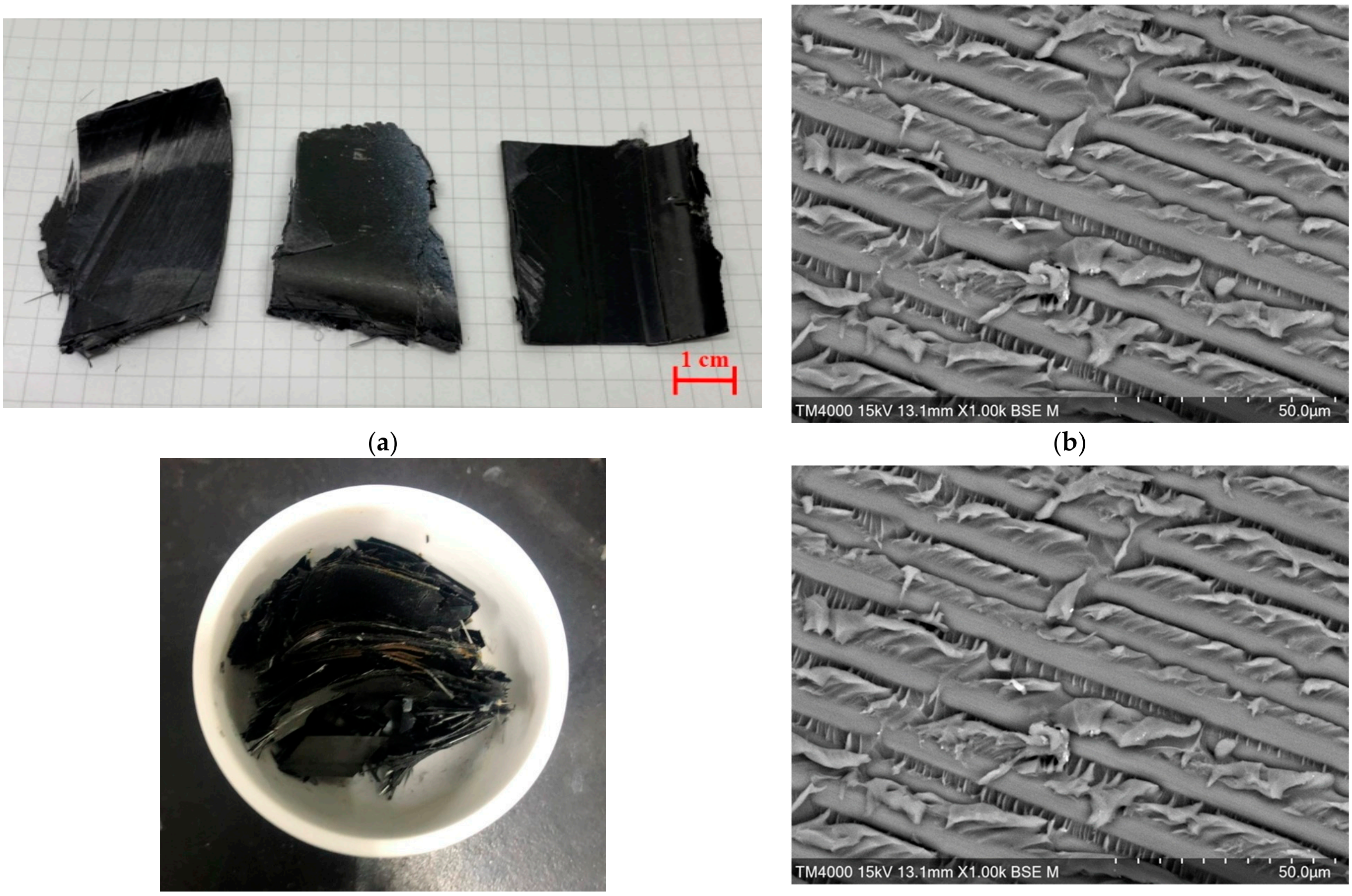


Figure 4. The load–displacement curves of the single filament tensile test: (**a**) Normal carbon fiber, (**b**) Recycled carbon fiber.

The single filament tensile test results show that the tensile strength of recycled carbon fiber treated with MAP is similar to that of the normal carbon fiber. This proves that MAP technology can effectively recycle CFRP waste and retain its mechanical strength.

2.4. SEM Surface Morphology of Carbon Fiber

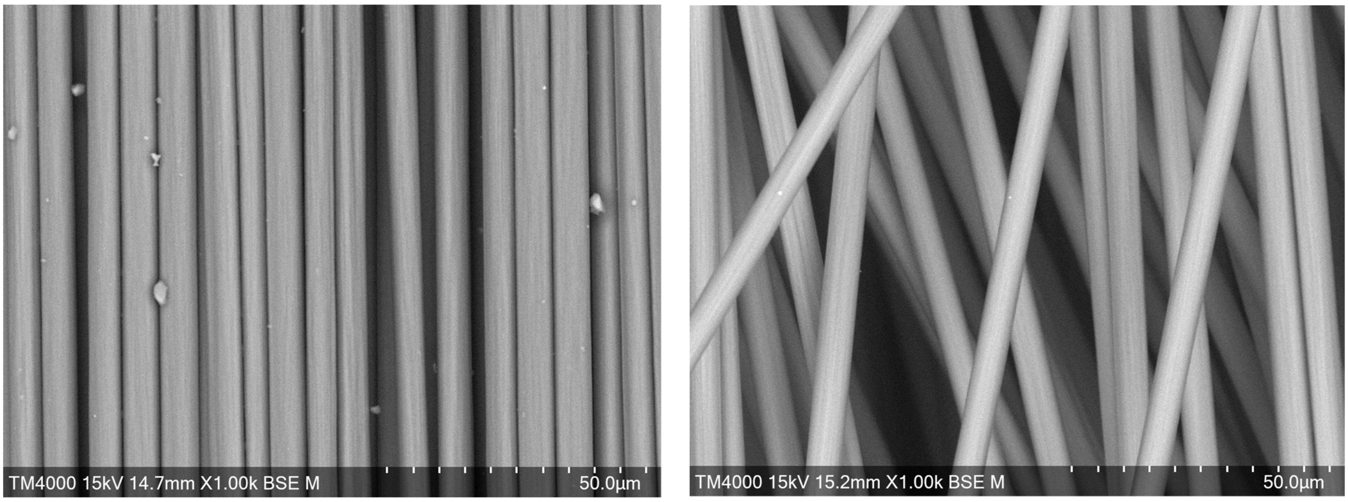
In order to understand the cleanliness of the resin on the surface of the recycled carbon fiber, in addition to observing the samples before and after the MAP treatment with a scanning electron microscope (SEM), energy dispersive X-ray spectrometry (EDS) was also used to observe the amount of removal. Figure 5a–d shows the photos and SEM images of the waste (recycled) CFRP before and after MAP technology. Using EDS to measure the carbon content of the carbon fiber, the carbon content of the recycled carbon fiber after MAP technology was 99.8%. The SEM image is shown in Figure 5d.



(**a**) (**b**) (**c**) (**d**)

Figure 5. Photos and SEM images of fragment samples of recycled carbon fiber composite materials. (**a**) Fragment samples of recycled CFRP before MAP technology; (**b**) SEM image before MAP technology; (**c**) fragment samples of recycled CFRP after MAP technology; (**d**) SEM image after MAP technology.

The surface morphology of the chopped carbon fiber with and without coupling agent was analyzed by scanning electron microscope (model: JSM-7610F, JEOL, Tokyo, Japan) in the Department of Molecular Science and Engineering Laboratory of the National Taipei University of Technology, Taipei, Taiwan. The surfaces of normal carbon fiber (with coupling agent) and carbon fiber without coupling agent were observed, and their SEM images are shown in Figure 6. Using EDS to measure the carbon content of the carbon fiber, the carbon contents of the normal carbon fiber with and without furnace heating process were 100% and 99.2%, respectively. The coupling agent on the surface of the carbon fiber might have interfered with the bonding strength between the carbon fiber and cement by the furnace heating method.



(**a**) (**b**)

Figure 6. SEM observation results of the surface of normal carbon fiber and carbon fiber without coupling agent. (**a**) SEM image of the chopped carbon fiber without furnace heating; (**b**) SEM image of the chopped carbon fiber with furnace heating.

2.5. Carbon Fiber-Reinforced Concrete

Carbon fiber is a non-corrodible material. The CFRC can reduce the cracks during the service life of concrete structures, it can preserve the steel rebar from corrosions, and mitigate impact loading. In this study, Portland cement was obtained from the Taiwan Cement Corporation [35]. The concrete (benchmark) and CFRC specimens were tested under compressive, three-point bending, and impact tests. The concrete water–cement ratio was 0.6; the cement, sand, fine aggregate, and coarse aggregate ratio was 1:1.05:1.5:0.75. The fineness modulus of the fine aggregate (3/8″) and coarse aggregate (6/8″) were 3.03 and 7.33, respectively. The fineness modulus (F.M.) of both aggregates for the concrete specimen was 6.01, as shown in Table 2. The concrete and CFRC specimens were cured at 28 days.

Table 2. Fineness modulus of aggregates.

Sieve No.	Weight Retained (g)	Percent Retained (%)	Cumulative Percent Retained (%)
3/2″	0	0	0
3/4″	672.3	23	23
3/8″	1352.4	46.2	69.2
No. 4	10.2	0.3	69.5
No. 8	165.6	5.7	75.2
No. 16	236.7	8.1	83.3
No. 30	178.2	6.1	89.4
No. 50	146.7	5	94.4
No. 100	83.7	2.9	97.3
Pan	79.2	2.7	100
Total	2925	-	Cumulative = 6.01

3. Experimental Methods and Setups

In this study, the CFRC specimens were prepared using three kinds of carbon fiber (recycled carbon fiber, normal carbon fiber, and carbon fiber without coupling agent). The compressive test, flexural test, and impact test followed the ASTM and ACI standards.

3.1. Experiment Planning

The three types of carbon fiber (normal carbon fiber, recycled carbon fiber, and carbon fiber without coupling agent) were planned to be used to prepare CFRC specimens with three different fiber weight proportions (5‰, 10‰, and 15‰), and the specimen names and descriptions, and the planning of the specimens are shown in Tables 3 and 4, respectively. For example, specimen C-R05 represents the compression test of recycled carbon fiber with the addition of 5‰ weight proportion.

Table 3. The naming and descriptions of CFRC specimens.

Naming	Description
C	compressive test
F	flexural test
I	impact test
B	benchmark (without carbon fiber)
N	carbon fiber with coupling agent
W	carbon fiber without coupling agent
R	recycled carbon fiber
Weight proportion (‰)	5, 10, 15

Table 4. Planning of CFRC specimens.

Experiment	Fiber Weight Proportion (‰)	Carbon Fiber			Benchmark	Total
		Normal	Recycled	Without Coupling Agent		
Compressive test	5	3	3	3	3	30
	10	3	3	3		
	15	3	3	3		
Flexural test	5	3	3	3	3	30
	10	3	3	3		
	15	3	3	3		
Impact test	10	25	25	25	25	100

3.2. Slump Test

The workability of the fiber-reinforced concrete has a significant impact on the construction quality, and good workability will prevent honeycombs in the concrete that reduce its strength. In this study, the slumps of CFRC of different types of carbon fiber and different weight proportions were tested according to ASTM C143/C143M−20; the slump fluidity range was about 15–230 mm, respectively [36].

3.3. Compressive Test

To explore the compressive strength of the three types of CFRC with different fiber additions, the dispersed chopped carbon fiber was mixed into concrete at a cement weight ratio of 5‰, 10‰, and 15‰. The diameter of the CFRC cylindrical specimen was 10 cm and the height was 20 cm. According to ASTM C39/C 39M-01 [37], the universal testing machine (HT-9501 Series. Hong-Ta, Taipei, Taiwan) was used for testing.

3.4. Three-Point Bending Test

According to ASTM C293-02 [38], the bending test of 28 cm × 7 cm × 7 cm CFRC specimens was carried out by a universal testing machine (HT-9501 Series. Hong-Ta, Taipei, Taiwan) with a load cell (WF 17120, Wykeham Farrance, Milan, Italy). The bending specimen was tested in the material laboratory of the Department of Civil and Disaster Prevention Engineering, National Taipei University of Technology. The three-point bending test is shown in Figure 7.

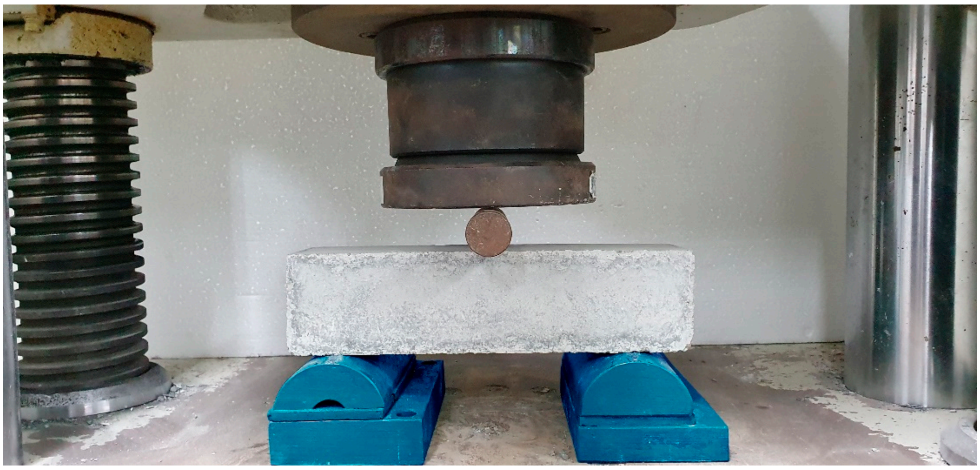


Figure 7. CFRC specimen flexural test setup.

3.5. Impact Test

According to ACI 544-2R [39], the impact test of ϕ150 mm $\times$ 64 mm CFRC specimens was carried out by impact equipment (SP-006, Sheng Peng, Yunlin, Taiwan). The impact energy was 25 J as the interval, and the number of repeated impacts was measured from 50 to 150 J. Figure 8a shows the impact specimen and impact device, and Figure 8b shows the impact test equipment.

(**a**) (**b**)

Figure 8. Impact test: (**a**) CFRC with impact device, (**b**) impact test equipment.

4. Experimental Results and Discussions

Three types of CFRC specimens were prepared from different fibers (recycled carbon fiber, normal carbon fiber, and carbon fiber without coupling agent). The test results of compressive, bending, and impact performance were obtained with the different kinds of carbon fiber in CFRC specimens. The recycled carbon fibers were fabricated by a scrap of CFRP bicycle frame with a MAP technology. The recycled carbon fiber was adopted from Thermolysis Co., Ltd. (Kao-Hsiung, Taiwan) [40]. The recycled carbon fiber was chopped to a length between 20 and 30 mm. The microwave conditions were established according to the process in Section 2.3.

4.1. Slump Test Result

The workability depends on the w/c ratio and weight proportions of fibers. The slump values of CFRC with different types of carbon fiber and different weight proportions are shown in Table 5. The test results showed that the slump value was not affected by the types of carbon fibers but affected by different weight proportions. The recycled carbon fiber with a length of 20–30 mm had a slight variation in the slump according to carbon fiber coupling agent presence and absence. The CFRC with 5‰ fiber weight proportion of the carbon fiber had the best workability, and its slump was about 160 mm. The CFRC with 15‰ fiber weight proportion of the carbon fiber became stickier, making the CFRC wet mixing hard to mix and sometimes diminished its mechanical strength. The CFRC mixture with more than 15‰ weight proportion had less workability under 0.60 w/c ratio.

Table 5. Slump test of different fiber weight proportions.

Fiber Weight Proportion (‰)	Slump of CFRC (mm)		
	Recycled	Normal	Carbon Fiber without Coupling Agent
0	230	230	230
5	160	165	165
10	85	80	80
15	40	40	40

4.2. Compressive Test Result

In this study, the three different kinds of carbon fiber-reinforced concrete were subjected to compression test by uniaxial loading. Figure 9 shows the average compressive strength of CFRC and benchmark under different proportions. Compared with other fiber weight proportions, adding 10‰ fiber weight proportion of CFRC can increase the maximum compressive strength.

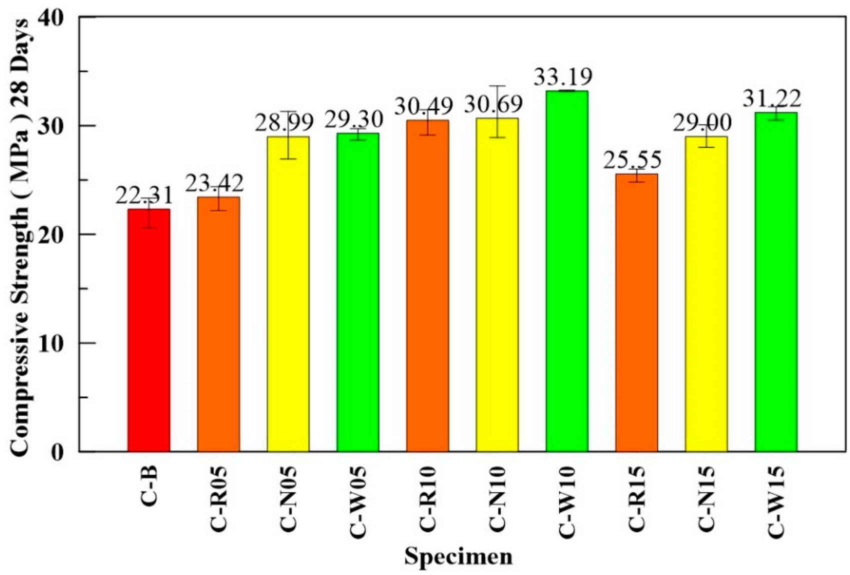


Figure 9. Average compressive strength of CFRC and benchmark specimens. (Note: C—Compression test; B—Benchmark; R—Recycled carbon fiber; N—Normal carbon fiber; W—Carbon fiber without coupling agent).

Table 6 shows the compressive strength of different CFRC and benchmark under different fiber weight proportions. Under three different carbon fiber weight proportions, the recycled carbon fiber-reinforced concrete and normal carbon fiber-reinforced concrete did not exhibit a greater enhancement effect on compressive strength than the carbon fiber-reinforced concrete by removing the coupling agent. For instance, the C-W10 specimen exhibited the highest compressive strength (33.19 MPa) compared with C-B specimen, C-N10 (30.69 MPa), and C-R10 (30.49 MPa), as shown in Table 6.

Table 6. Compressive strengths of CFRC and benchmark under different proportions.

Specimen	Number	Compressive Strength (MPa)	Average (MPa)	Increase (%)
C-B	1	20.60	22.31	-
	2	23.32		
	3	22.99		
C-R05	1	22.19	23.42	4.9
	2	23.69		
	3	24.39		
C-N05	1	26.94	28.99	29.9
	2	31.32		
	3	28.72		
C-W05	1	29.49	29.30	31.3
	2	28.68		
	3	29.72		
C-R10	1	30.87	30.49	36.7
	2	31.47		
	3	29.14		
C-N10	1	33.65	30.69	37.6
	2	29.50		
	3	28.91		
C-W10	1	33.27	33.19	48.9
	2	33.15		
	3	33.15		
C-R15	1	25.84	25.55	14.5
	2	26.01		
	3	24.81		
C-N15	1	30.08	29.00	30
	2	28.93		
	3	28.00		
C-W15	1	31.73	31.22	39.9
	2	31.42		
	3	30.52		

Note: C—Compression test; B—Benchmark; R—Recycled carbon fiber; N—Normal carbon fiber; W—Carbon fiber without coupling agent.

When the fiber weight proportion was 10‰, the compressive strength of specimen C-W10 was the highest, followed by specimen C-N10 and specimen C-R10. Using EDS to measure the carbon content of the carbon fiber, the carbon contents of the normal carbon fiber with the furnace heating process, the recycled carbon fiber with the MAP process, and the normal carbon fiber were 100, 99.8, and 99.2%, respectively. The test results showed that the higher the carbon content of the carbon fibers, the higher the compressive strength of the CFRC specimen. The surface of the carbon fiber without coupling agent or resin residual, the adhesion force between carbon fiber and cement increased. Therefore, the CFRC specimen without coupling agent (C-W10) has the highest compressive strength.

4.3. Three-Point Bending Test Result

In this Subsection, the flexural strength of three kinds of CFRC with different fiber weight proportions are compared with the benchmark specimens. As shown in Figure 10, the CFRC with 10‰ of fiber weight proportion increased its flexural strength more than the other fiber weight proportions, such as 5‰ and 15‰. From the slump test results, the 15‰ fiber weight proportion of CFRC was close to the lower range compared with the ASTM C143/C143M-20 standard requirement (mention in Section 3.2), respectively. Therefore, the carbon fibers were not easy to distribute uniformly in the FRC, and the flexural strength was reduced. Additionally, the CFRC with 5‰ fiber weight proportion of carbon fiber was not enough to increase the flexural strength because the amount of carbon fiber was too low.

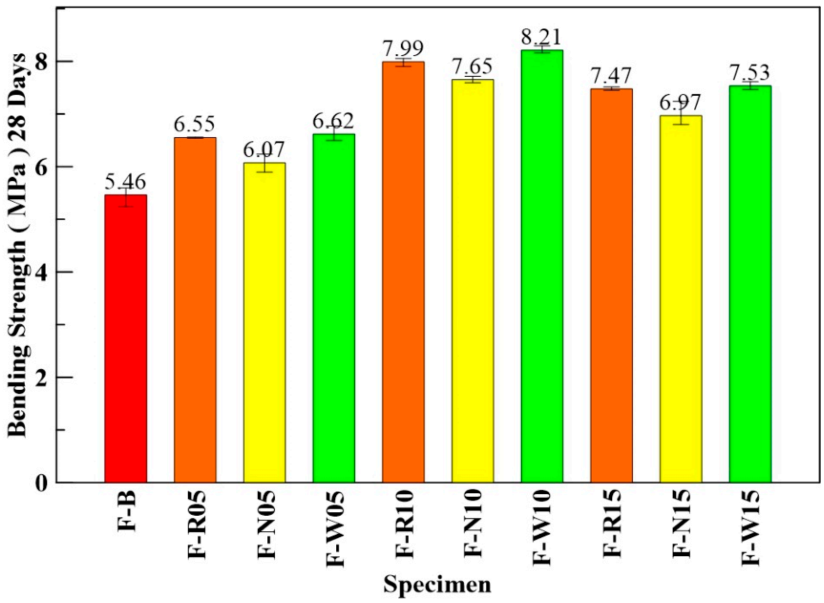


Figure 10. Average flexural strengths of CFRC and benchmark specimens. (Note: F—Flexural; B—Benchmark; R—Recycled carbon fiber; N—Normal carbon fiber; W—Carbon fiber without coupling agent).

Table 7 shows the flexural strength of CFRC and benchmark under different fiber weight proportions. The F-W10 specimen increased its flexural strength up to 50.4% compared with F-B specimen. Similarly, the flexural strength of F-R10 and F-N10 had higher strength than the benchmark specimen at 46.3 and 39.6%, respectively. In Section 2.4, the SEM images with the corresponding EDS showed the carbon content of carbon fiber without coupling agent, recycled carbon fiber, and normal carbon fiber were 100, 99.8, and 99.2%, respectively. As seen from the flexural test results and the EDS measurement, the flexural strength increased with the carbon contents of the carbon fiber; the fewer residuals increased the flexural strength of the CFRC specimens.

Table 7. Flexural strengths of CFRC and benchmark under different proportions.

Specimen	Number	Compressive Strength (MPa)	Average (MPa)	Increase (%)
F-B	1	5.55	5.46	-
	2	5.60		
	3	5.24		
F-N05	1	5.90	6.07	11.2
	2	6.24		
	3	6.08		
F-R05	1	6.55	6.55	20.0
	2	6.54		
	3	6.56		
F-W05	1	6.77	6.62	21.2
	2	6.50		
	3	6.58		
F-N10	1	7.65	7.62	39.6
	2	7.59		
	3	7.72		
F-R10	1	8.00	7.99	46.3
	2	7.90		
	3	8.06		
F-W10	1	8.29	8.21	50.4
	2	8.18		
	3	8.16		
F-N15	1	7.24	6.97	27.7
	2	6.86		
	3	6.80		
F-R15	1	7.46	7.47	36.6
	2	7.51		
	3	7.45		
F-W15	1	7.52	7.53	37.9
	2	7.61		
	3	7.46		

Note: F—Flexural; B—Benchmark; R—Recycled carbon fiber; N—Normal carbon fiber; W—Carbon fiber without coupling agent).

4.4. Impact Test Result

The impact numbers of benchmark and CFRC specimens under different impact energies are shown in Table 8. From the test results, the I-N10, I-R10, I-W10 specimens resisted repeated impact at low energy of 50 J and the average impact numbers were about 285, 356, and 410, respectively. Compared with the I-B specimen, the I-N10, I-R10, and I-W10 specimens and the impact number increase percentages were about 1828%, 2305% and, 2669%, respectively. From the impact test result, the CFRC specimens with recycled carbon fiber and carbon fiber without coupling agent exhibited enhancement effects compared to the CFRC specimen with normal carbon fiber.

Table 8. Impact test results of CFRC specimens under different impact energies.

Specimen	Impact Energy (J)	Specimen Number					Average Impact Number	Increase Percentage (%)
		1	**2**	**3**	**4**	**5**		
I-B	150	1	1	1	1	1	1.0	-
	125	2	2	2	2	3	2.2	-
	100	3	3	4	4	4	3.6	-
	75	5	6	6	7	7	6.2	-
	50	13	14	15	16	16	14.8	-
I-N10	150	1	1	1	2	2	1.4	40.0
	125	3	3	4	4	4	3.6	63.6
	100	10	11	13	14	15	12.6	250.0
	75	53	60	62	63	66	60.8	880.6
	50	267	275	288	293	304	285.4	1828.4
I-R10	150	1	1	2	2	2	1.6	60.0
	125	3	4	4	4	4	3.8	72.7
	100	16	17	18	19	19	17.8	394.4
	75	74	76	87	88	91	83.2	1241.9
	50	338	349	353	366	374	356	2305.4
I-W10	150	1	2	2	2	2	1.8	80
	125	3	4	4	4	5	4.0	81.8
	100	16	16	18	19	21	18	400.0
	75	78	81	86	92	98	87	1303.2
	50	385	392	409	429	434	409.8	2668.9

Note: I—Impact; B—Benchmark; N—normal carbon fiber; R—recycled carbon fiber; W—carbon fiber without coupling agent.

Figure 11 shows the impact energy/number curve of CFRC specimens. It can be clearly seen that the repeated impact number of CFRC specimens under low impact energy is greater than that under high impact energy.

As seen in Figure 11, the I-W10 specimen had the highest average number of repeated impacts when the impact energy was 50 J, followed by I-R10 and I-N10. The EDS measurement results and impact test results show that the higher carbon contents of the carbon fiber had higher repeated impact capability of CFRC.

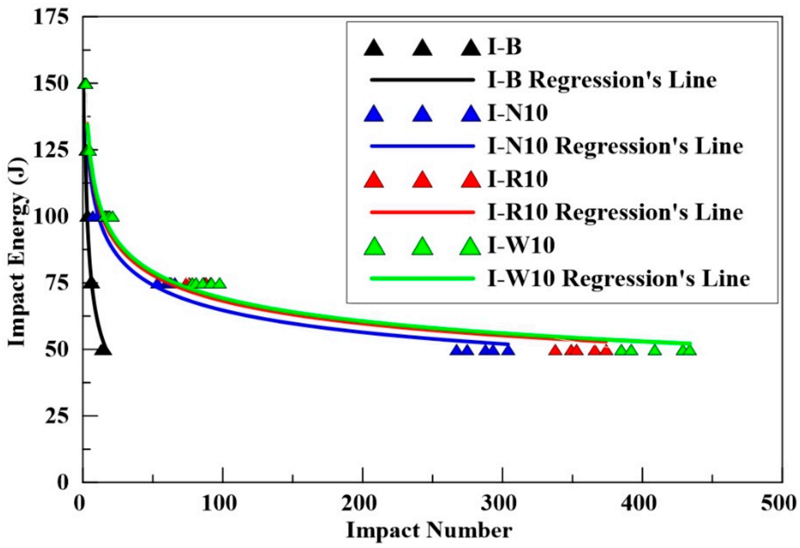


Figure 11. The curves of impact energy/number of CFRC specimens. (Note: I—Impact; B—Benchmark; N—Normal carbon fiber; R—Recycled carbon fiber; W—Carbon fiber without coupling agent).

5. Conclusions

Regarding the CFRC with different proportions of normal carbon fiber, recycled carbon fiber, and carbon fiber without coupling agent under static and impact tests several conclusions can be stated as follows.

1. According the SEM-EDS, the carbon content on the surface of recycled carbon fiber was about 99.8% with the MAP technology process, which effectively removed the resin to revert the carbon fiber of the CFRP product. In addition, the carbon content for normal carbon fiber and carbon fiber without coupling agent were about 99.2 and 100%, respectively.
2. The test results showed that the slump value was not affected by the carbon fibers but affected by different weight proportions.
3. The 10‰ proportion carbon fiber without coupling agent exhibited maximum compressive strength compared with the benchmark, recycled, and normal carbon fiber. The maximum compressive strengths of the C-W10, C-R10, and C-N10 specimens were compared with the C-B specimen, and the increased percentages were about 48.8%, 37.6%, and 36.7%.
4. The CFRC with 10‰ fiber weight proportion increased its flexural strength compared with other proportions because the 5% was not enough to increase the strength compared with 10%, and the 15% proportions were too close to the lowest slump value (mm) in the standard. The high fiber weight proportion made the CFRC difficult to mix and reduced its strength.
5. From the impact test, the CFRC with the absence of coupling agent (I-W10) had high impact resistance, and then recycled (I-R10) had a high impact resistance number compared to carbon fiber with the presence of coupling agent (I-N10) under different energies (J).
6. According to the test results, the flexural strengths and impact resistances of the CFRC specimens were closely related to the carbon content of carbon fiber measured by EDS. We saw from the experiment that the higher carbon content had higher flexural strength and higher impact resistance.
7. The mechanical performance of recycled carbon fiber was superior to the normal carbon fiber, and it was almost similar to the carbon fiber-reinforced concrete by removal of silane. Using the MAP approaches, the waste scrap of CFRP can be

recycled to carbon fibers and applied to reinforced structures such as bridge expansion joints, tunnels, dams, airport and highway pavements, etc.

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References

1. Erdem, S.; Hanbay, S.; Blankson, M.A. Self-sensing damage assessment and image-based surface crack quantification of carbon nanofiber reinforced concrete. Constr. *Build. Mater.* **2017**, *134*, 520–529. [CrossRef]
2. Li, Y.; Li, Y. Experimental study on performance of rubber particle and steel fiber composite toughening concrete. *Constr. Build. Mater.* **2017**, *146*, 267–275. [CrossRef]
3. Giner, V.T.; Baeza, F.J.; Ivorra, S.; Zornoza, E.; Galao, O. Effect of steel and carbon fiber additions on the dynamic properties of concrete containing silica fume. *Mater. Des.* **2012**, *34*, 332–339. [CrossRef]
4. Nili, M.; Afroughsabet, V. Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete. *Int. J. Impact Eng.* **2010**, *37*, 879–886. [CrossRef]
5. Naraganti, S.R.; Pannem, R.M.R.; Putta, J. Impact resistance of hybrid fibre reinforced concrete containing sisal fibres. *Ain Shams Eng. J.* **2019**, *10*, 297–305. [CrossRef]
6. Chen, P.W.; Chung, D.D.L. Concrete reinforced with up to 0.2 vol% of short carbon fibres. *Composites* **1993**, *24*, 33–52. [CrossRef]
7. Li, V.C.; Obla, K.H. Effect of fiber length variation on tensile properties of carbon-fiber cement composites. *Compos. Eng.* **1994**, *4*, 947–964. [CrossRef]
8. Park, S.-J.; Seo, M.-K.; Shim, H.-B.; Rhee, K.Y. Effect of different cross-section types on mechanical properties of carbon fibers-reinforced cement composites. *Mater. Sci. Eng. A* **2014**, *366*, 348–355. [CrossRef]
9. Tabatabaei, Z.S.; Volz, J.S.; Keener, D.I.; Gliha, B.P. Comparative impact behavior of four long carbon fiber reinforced concretes. *Mater. Des.* **2014**, *55*, 212–223. [CrossRef]
10. Rangelov, M.; Nassiri, S.; Haselbach, L.; Englund, K. Using carbon fiber composites for reinforcing pervious concrete. *Constr. Build. Mater.* **2016**, *126*, 875–885. [CrossRef]
11. Meng, W.; Khayat, K.H. Mechanical properties of ultra-high-performance concrete enhanced with graphite nanoplatelets and carbon nanofibers. *Compos. B Eng.* **2016**, *107*, 113–122. [CrossRef]
12. Han, B.; Zhang, L.; Zhang, C.; Wang, Y.; Yu, X.; Ou, J. Reinforcement effect and mechanism of carbon fibers to mechanical and electrically conductive properties of cement-based materials. *Constr. Build. Mater.* **2016**, *125*, 479–486. [CrossRef]
13. Li, Y.-F.; Lee, K.-F.; Kadagathur Ramanathan, G.; Cheng, T.-W.; Huang, C.-H.; Tsai, Y.-K. Static and Dynamic Performances of Chopped Carbon-Fiber-Reinforced Mortar and Concrete Incorporated with Disparate Lengths. *Materials* **2021**, *14*, 972. [CrossRef] [PubMed]
14. Xu, Y.; Chung, D. Carbon fiber reinforced cement improved by using silane-treated carbon fibers. *Cem. Concr. Res.* **1999**, *29*, 773–776. [CrossRef]
15. Yang, Y. Methods Study on Dispersion of Fibers in CFRC. *Cem. Concr. Res.* **2001**, *32*, 747–750. [CrossRef]
16. Wang, Z.; Gao, J.; Ai, T.; Jiang, W.; Zhao, P. Quantitative evaluation of carbon fiber dispersion in cement based composites. *Constr. Build. Mater.* **2014**, *68*, 26–30. [CrossRef]
17. Gao, J.; Wang, Z.; Zhang, T.; Zhou, L. Dispersion of carbon fibers in cement-based composites with different mixing methods. *Constr. Build. Mater.* **2017**, *134*, 220–227. [CrossRef]
18. Li, Y.-F.; Yang, T.-H.; Kuo, C.-Y.; Tsai, Y.-K. A Study on Improving the Mechanical Performance of Carbon-Fiber-Reinforced. *Cement. Mater.* **2019**, *12*, 2715. [CrossRef] [PubMed]
19. Saxena, R.; Siddique, S.; Gupta, T.; Sharma, R.K.; Chaudhary, S. Impact resistance and energy absorption capacity of concrete containing plastic waste. *Constr. Build. Mater.* **2018**, *176*, 415–421. [CrossRef]

20. Saikia, N.; de Brito, J. Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Constr. Build. Mater.* **2014**, *52*, 236–244. [CrossRef]
21. Ankur, C.; Narendra, K. Impact strength, permeability and chemical resistance of concrete reinforced with metalized plastic waste fibers. *Constr. Build. Mater.* **2018**, *161*, 254–266.
22. Li, G.; Stubblefield, M.; Garrick, G.; Eggers, J.; Abadie, C.; Huang, B. Development of waste tire modified concrete. *Cem. Concr. Res.* **2004**, *34*, 2283–2289. [CrossRef]
23. Zhong, H.; Zhang, M. Experimental study on engineering properties of concrete reinforced with hybrid recycled tyre steel and polypropylene fibres. *J. Clean. Prod.* **2020**, *259*, 120914. [CrossRef]
24. García, D.; Vegas, I.; Cacho, I. Mechanical recycling of GFRP waste as short-fiber reinforcements in microconcrete. *Constr. Build. Mater.* **2014**, *64*, 293–300. [CrossRef]
25. Rodin III, H.; Nassiri, S.; Englund, K.; Fakron, O.; Li, H. Recycled glass fiber reinforced polymer composites incorporated in mortar for improved mechanical performance. *Constr. Build. Mater.* **2018**, *187*, 738–751. [CrossRef]
26. Mastali, M.; Dalvand, A.; Sattarifard, A. The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fibre reinforced polymers. *J. Clean. Prod.* **2016**, *124*, 312–324. [CrossRef]
27. Ogi, K.; Shinoda, T.; Makoto, M. Strength in concrete reinforced with recycled CFRP pieces. *Compos. A Appl. Sci.* **2005**, *36*, 893–902. [CrossRef]
28. Mastali, M.; Dalvand, A. The impact resistance and mechanical properties of self-compacting concrete reinforced with recycled CFRP pieces. *Compos. B Eng.* **2016**, *92*, 360–376. [CrossRef]
29. Nguyen, H.; Fujii, T.; Okubo, K.; Carvelli, V. Cement mortar reinforced with recycled carbon fiber and CFRP waste. In Proceedings of the ECCM17—17th European Conference on Composite Materials, München, Germany, 26–30 June 2016.
30. Sheng Peng Applied Materials Co., Ltd. Available online: http://www.spco.com.tw/index.aspx?lang=US (accessed on 18 March 2021).
31. Tairylan Division, FPG. Available online: http://www.jeccomposites.com/directory/formosa-plastics-corporation (accessed on 8 January 2021).
32. Yin, C. Microwave-assisted pyrolysis of biomass for liquid biofuels production. *Bioresour. Technol.* **2012**, *120*, 273–284. [CrossRef]
33. Motasemi, F.; Afzal, M.T. A review on the microwave-assisted pyrolysis technique. *Renew. Sustain. Energy Rev.* **2013**, *28*, 317–330.
34. ASTM D3379. *Standard Test Method for Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials*; ASTM Annual Book of Standards; ASTM: West Conshohocken, PA, USA, 1989; pp. 128–131.
35. Taiwan Cement Corporation. Available online: https://www.taiwancement.com/en/aboutProduct.html (accessed on 22 February 2021).
36. ASTMC143/C143M-20. *Standard Test Method for Slump of Hydraulic–Cement Concrete*; ASTM: West Conshohocken, PA, USA, 2015.
37. ASTM C39/C39M-01. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*; ASTM: West Conshohocken, PA, USA, 2012.
38. ASTM C293-02. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)*; ASTM: West Conshohocken, PA, USA, 2010.
39. ACI-544-2R89. *Measurement of Properties of Fiber Reinforced Concrete*; America Concrete Institute: Farmington Hills, MI, USA, 1999; pp. 6–7.
40. Thermolysis Co., Ltd. Available online: https://www.thermolysis-asia.com/ (accessed on 18 March 2021).