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Pet Fiber Reinforced Wet-Mix Shotcrete with Walnut Shell as Replaced Aggregate

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Academic Editor: Stefano Invernizzi
Received: 1 February 2017; Accepted: 29 March 2017; Published: 31 March 2017

Abstract: In the rapidly developing modern society, many raw materials, such as crushed limestone and river sand, which are limited, are consumed by the concrete industry. Naturally, the usage of waste materials in concrete have become an interesting research area in recent years, which is used to reduce the negative influence of concrete on the environment. Hence, this paper presents the development of a sustainable lightweight wet-mix shotcrete by replacing natural coarse gravel with a kind of byproduct, nut shell (walnut). Fibers made from dumped polyethylene terephthalate (PET) bottles were mixed in the composite to improve the properties of the lightweight wet-mix shotcrete. The initial evaluation of the fresh concrete mixed with different volume fraction of walnut shell was carried out in terms of its performance capacities of mechanical properties (i.e., tensile and compressive strength), pumpability and shootability (i.e., slump, pressure drop per meter and rebound rate) and the results were compared with plain concrete. With increase of walnut shell, compressive and splitting tensile strength of casting concrete decreased, while slump and pressure drop reduced slightly. Additionally, appropriate dosage of walnut shell can improve the shootability of fresh concrete with low rebound rate and larger build-up thickness. In the second series tests, polypropylene (PP) fiber and multi-dimension fiber were also mixed in composite for comparative analysis. After mixing fibers, the splitting tensile strength had obtained marked improvement with slight reduction of compressive strength, along with acceptable fluctuation in terms of pumpability and shootability. Furthermore, relation of density and compressive strength, relation of rebound and density, build-up thickness and relation of compressive and splitting tensile strength were discussed. This study found wet-mix shotcrete incorporating PET fiber with walnut shell of about 35% coarse aggregate replacement could be used for roadway support as lightweight shotcrete per requirements of mine support.

Keywords: wet-mix shotcrete; walnut shell; PET fiber; mechanism; pumpability; shootability

1. Introduction

The support technology of bolt steel mesh shotcrete is widely used in modern mine roadways [1,2]. Therein, shotcrete, also called sprayed concrete, is a special cement-based mixture that is designed and projected pneumatically at a high velocity towards a target surface [3,4]. Further, it is necessary that shotcrete be compacted by its own momentum, especially when sprayed on the roof [5,6]. Otherwise, miners working under the roof sprayed with concrete would be not safe, being threaten by falling concrete bulk due to the huge self-weight of shotcrete or low adhesion stress between matrix and concrete. Therefore, in terms of the weight of concrete, lightweight shotcrete should be developed and used to reduce the debond of shotcrete from matrix and also avoid casualties resulted from dropped shotcrete.

Lightweight shotcrete has been developed for many years, and made by mixing air entraining agent or lightweight aggregates [7,8]. Because excavating aggregates from natural sources such as quarries and river bed have resulted in severe environment problems including pollution of air, soil and water and breaking of the ecosystem [9,10], the development more optimal eco-friendly concrete was proposed; therefore, studies on waste materials and industrial byproducts, such as scoria, pumice, oil palm kernel shell, plastic particles and recycled aggregates, as a kind of coarse or fine aggregate, are being widely researched [11–14]. Attempts have been made by various researchers to decrease the density of concrete without affecting the strength. For example, Yang et al. [15,16] investigated the recycling possibilities for crushed oyster shells in order to reduce coarse and fine aggregate usage, and results showed that the strength of concrete with 10% oyster shells replacement was almost equal to that of normal concrete. One recent research explored the use of lightweight fiber-cement composite mixed with rice stalk fiber (as reinforcement) and rice husk ash (as cement replacement) that are agricultural byproducts, test results indicated cement boards made with rice stalk fiber had superior properties compared to those mixed with hardwood fibers [17]. Some researchers investigated the performance of lightweight concrete with oil palm kernel shell as lightweight aggregate and found that a compressive strength between 13 and 30 MPa can be achieved [18].

According to those studies, experiments are needed to solve the problem of how to increase the substitution ratio in shotcrete mixtures to make sure the final performance of the material. Nutshell is a wood byproduct obtained during the extraction of seeds, such as walnut, which is abundantly available in food processing factories in China. According to previous research, walnut shells were mixed into a protective floor topping composition for improving the wear resistance of floors which were subjected to heavy compressive loads [19–21]. In addition, a new type of cement composition was reported in the literature [22], which mainly consisting of two materials, wherein the first material of particles included at least one of ground, crushed fruit pits or processed wood. Walnut shells were also used for processing composite particleboard to improve its requirements such as water resistance features by mixing fly ash and the optimal results indicated that maximum bending strength can reach up to 3.8 N/mm^2 [23]. M. Zahedi et al. [24] evaluated the feasibility of almond shell as substitute to producing wood-plastic composites and indicated that almond shell as agro-waste material was a recyclable natural resource for composite industry. Due to the high hardness of walnut shell, walnut shell was treated as an abrasive that is applied to surface preparation on all types of cementitious surfaces including cast-in-place concrete floors and walls, masonry walls, and shotcrete surfaces [25,26]. Currently, there are no published reports describing the use of walnut shell as lightweight coarse aggregate in shotcrete.

The application of wet-mix shotcrete is prevalent in support in China because dry-mix shotcrete, producing a great deal of dust during processing, is forbidden in Chinese mine supports. Therefore, in this study, crushed walnut shells were selected as partial coarse aggregate substitute for wet-shotcrete. Tests of compression, splitting, slump, pressure drop along pipes, rebound rate and build-up thickness with different walnut shell amounts were preliminarily tested to ensure the feasibility of walnut shell as coarse aggregate replacement in shotcrete, while simultaneously determining the optimal mixture dosage.

Additionally, considering that plastic shrinkage cracks may occur especially in hostile environments underground that cannot normally reach the standard requirement for curing shotcrete, which may impair the durability and serviceability of shotcrete structures, fibers were added in shotcrete to prevent such cracks. Presently, instead of traditional fibers such as steel fiber, carbon, glass and polypropylene, many studies use waste plastic fibers to reinforce concrete based on the environmental protection concept [27–34]. As well known, fibers act as micro crack arrester as well as substantial energy absorption in cement composites; thus, in this study, the fibers obtained from waste polyethylene terephthalate (PET) bottles were applied to reinforce the lightweight wet-mix shotcrete to reduce the cost of shotcrete and somewhat solve waste disposal problem.

PET fiber has been applied to construction buildings such as spraying support in expressway tunnels, as reported by T. Ochi [35]; moreover, a method was described for producing PET fiber from waste PET bottles and the wetting tension of PET was measured. Mechanical properties of concrete containing PET fiber of 0.5%, 1.0% and 1.5% fraction volume were measured, including splitting tensile strength and compressive strength [36]. The results indicated that concrete mixed with proper PET fiber can enhance its performance, as reported in [37]. On the contrary, Kim et al. [38] revealed that recycled PET fiber-reinforced specimens showed compressive strength decreases of 1%–9% compared to plain concrete, while the elastic modulus of concrete with PET fiber slightly decreased with the increase of fiber volume fraction. Additionally, Irwan et al. [39] also indicated that the addition of PET fibers decreased the compressive strength and splitting tensile of concrete specimens. Fadhil and Yaseen [40] investigated the rupture strength and impact resistance of precast concrete panels with different volumes PET fiber from cutting the plastic beverage bottles by hand. The results showed that the percentage of increase of rupture strength and impact resistance was 34.27% and 157.14%, respectively, for reinforced concrete compared with plain panels. The influence of PET fibers geometry on the properties of concrete was investigated, Marthong and Sarma [41,42] showed that fiber geometry has a small effect on the workability of concrete but a significant contribution to the mechanical properties of concrete.

There is a great deal of active research on the mechanical properties of concrete with PET fiber, such as splitting tensile strength, compressive strength, rupture strength and elastic modulus and so on, however, research on shotcrete mixed with PET fiber is scarce, especially on the aspect of pumpability and shootability. To author's knowledge, literature [35] only indicated PET fiber content in concrete can be freely changed in situ without fiber-ball formation and pipe clogging but no describing about shootability of PET fiber shotcrete with walnut shell.

The aim of this study is to develop a type of lightweight wet-mix shotcrete with sufficient properties to meet the standards of mine supporting construction by adding PET fiber and walnut shell replacing natural coarse aggregates. Tests were divided two parts. In the first series, in order to develop an alternative material with eco-friendly idea, the initial evaluation of the fresh concrete mixed with different volume fraction of walnut shell was carried out in terms of its performance capacities of mechanical properties (i.e., tensile and compressive strength), pumpability and shootability (i.e., slump, pressure drop per meter and rebound rate). In the second series, to enhance its tensile strength, in addition to PET fiber, polypropylene (PP) fiber and multi-dimension fiber were also mixed in composite for comparative analysis. Finally, relationship of density and compressive strength, relationship of rebound and density, build-up thickness and relationship of compressive and splitting tensile strength were discussed to understand the change of properties of PET fiber reinforcement lightweight shotcrete well. The results of this study validated the possibility of using eco-friendly PET fiber as reinforcement and crushed walnut shell as aggregate replacement for wet-mix shotcrete used in roadway supporting.

2. Experimental Materials and Program

2.1. Experimental Materials

2.1.1. Cement and Aggregate

Ordinary Portland cement (OP.42.5) was used in these experiments which complied with Chinese standard GB175-2007 [43] with a chemical composition of 19.5% SiO_2, 6.45% Al_2O_3, 3.08% Fe_2O_3, 57.6% CaO, 1.3% MgO, and 2.01% SO_3. Natural river sand as fine aggregate was used in these tests with a specific gravity of 2.58 g/cm^3, and water absorption of 7.1%. The coarse aggregate was crushed gravel with continuous grading from 5 mm to 10 mm. The specific gravities and water absorption of the gravel are 2.64 g/cm^3 and 1.9%, respectively. Both sand and gravel complied with the requirement in GB50086-2001 [44].

In addition, walnut shell was used as a replacement of natural gravel. In this study, walnut shell was collected and crushed. Prior to using the crushed walnut shell, they were sieved into one size category, between 5 mm and 10 mm (passed through the 10 mm sieve and retained on the 5 mm sieve) as illustrated in Figure 1. Subsequently, they were washed to remove dirt before being air dried in the laboratory. Walnut shell is irregularly shaped (polygonal or flaky) with 1–4 mm thickness shown in Figure 1. The surfaces of convex portion of crushed shell are relatively smooth with rough surfaces than that of concave portion along the cracked edges. The specific gravities and water absorption of walnut shell are 1.02 g/cm^3 and 31.4%, respectively. According to tests of FTIR (Fourier Transform Infrared Spectroscopy) spectrum [45,46], some of the major constituents in walnut shell are lignin, cellulose and hemicellulose and the essential elements of walnut shell are C, H, O, N and S. Moreover, many beneficial elements such as Ca, K, Na, Fe and Mg were found in walnut shell by the method of plasma element emission. Mingzheng et al. [47] indicated that the critical force ranged 74.24–154.13 N from the analysis of thin shell theory as the crack of walnut shell occurred. The gradation curves for natural gravel, sand and crushed walnut shell are plotted in Figure 2. The specific gravity of walnut shell is obviously lower than that of the natural aggregate, while the walnut shell absorbs more water than natural aggregate. Hence, walnut shell can be termed as lightweight aggregate as it has low specific gravity.

Figure 1. The surfaces of crushed walnut shell and the process of sieving.

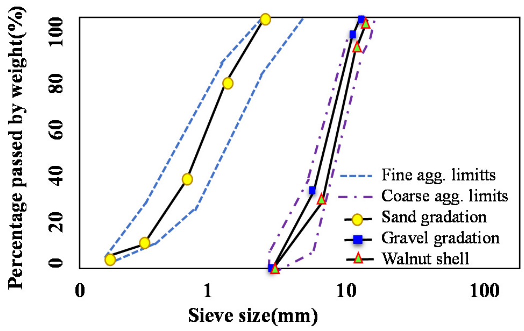

Figure 2. Gradation curves for natural gravel, sand and crushed walnut shell.

2.1.2. Fibers

The waste PET bottles were collected from household waste and were only treated by water-based washing. Then, the bottles were cut by hand or a mechanical cutting device, as reported in the literature [48,49], which is simplest and economic cutting method. The fiber dimensions were approximately 2–3 mm in width, 0.34 mm in thickness and lengths of 20–25 mm for fibers (Figure 3). The aspect ratio value of PET fiber used in tests is approximately 9. Different waste bottles (such as refreshing drinks, water, tea and juices) were measured [48,49]. The results showed that all the PET fiber samples basically had the same spectrum according to FTIR spectra tests, slight differences of crystallinity observed by tests of DSC (differential scanning calorimetry) thermograms, the Young's modulus and tensile strength of 3830 ± 47 MPa, 108 ± 15 MPa, respectively [48,49]. Thus, different waste bottles had a minor variation from one sample to another. For comparative analysis, normal polypropylene fiber (PP) in Figure 3 purchased from Taian Companion Fiber Co., Ltd. (Taian, China) was used in these tests with an elastic modulus of more than 3850 MPa, a tensile strength of more than 500 MPa and a length of 15 and 30 mm [50].

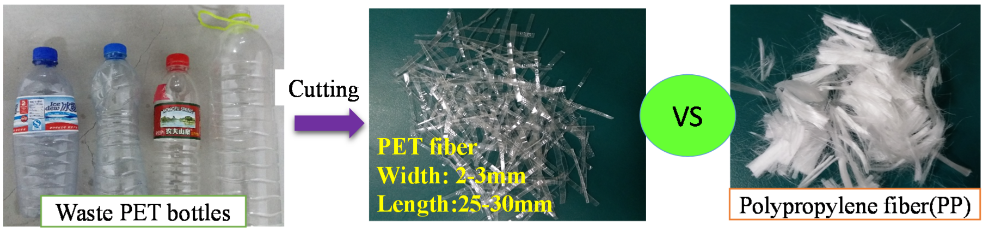

Figure 3. Cutting PET bottles for PET fiber and polypropylene fiber (PP).

2.1.3. Admixture

This study included silica fume with a specific surface area of 160,000–300,000 cm^2/g and a specific gravity of 2.21 g/cm^3. The silica fume consisted of up to 95% SiO_2 with less than 1% CaO. Rosin type air entraining agent purchased from Dongguan Deep-Sea Magnesium Foaming Agent Co., Ltd. (Dongguan, China), which can achieve an air content of 4.7% ± 2%.

2.2. Experimental Program

This research was separated into two parts: an initial evaluation of the fresh concrete mixed with different dosage walnut shell was carried out; and then a series of tests with fiber reinforcement lightweight shotcrete was conducted. Both series include the following tests.

2.2.1. Tests of Mechanical Properties

In the first series tests, before spraying, specimens of fresh concrete only with crushed walnut shell were directly cast into steel molds in Figure 4a with dimensions 100 mm × 100 mm × 100 mm to measure the compressive strength and splitting tensile strength. According to Chinese Standard of GB/T 50081-2002 [51], 100 mm test cube as a kind of nonstandard specimen can be used for splitting tensile tests.

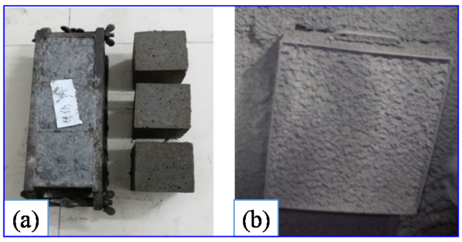

Figure 4. Casting concrete into steel molds (**a**); and spraying into a mold (**b**).

Additionally, the production steps of shotcrete specimens were as follow: The fresh concrete was firstly sprayed into iron box molds with dimensions of 450 mm × 350 mm × 120 mm using wet-mix shotcrete method shown in Figure 4b. After 1 day curing in a standard curing chamber with temperature of 20 ± 2 °C and 95% relative humidity, specimens were demolded. The large concrete slabs were subsequently cut into nonstandard cube specimens with dimensions 100 mm × 100 mm × 100 mm after 7 days curing. Finally, specimens were cured at standard condition to 28 days. All specimens used for mechanical properties were prepared before and after shotcreting as per Chinese Standards of GB 50086-2001 [44] and GB 50164-2011 [52]. The uniaxial compressive strength and splitting tensile strength of specimens were measured using a WDW3100 computer-controlled electric universal test machine. Figure 5 indicates tests of compressive strength (Figure 5a), splitting tensile strength (Figure 5b) and measuring thickness of spraying layer (Figure 5c).

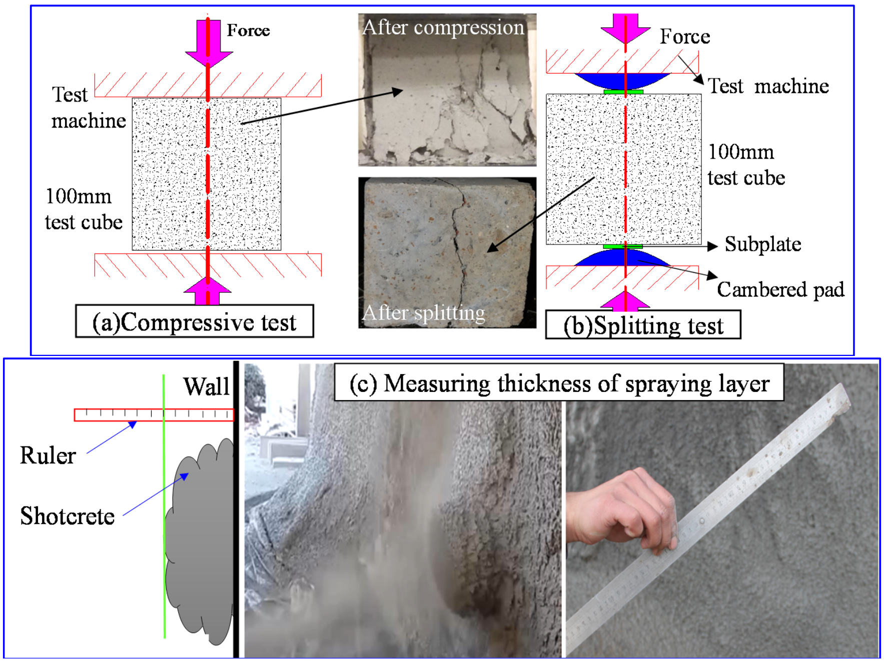

Figure 5. Tests of compressive strength (**a**); splitting tensile strength (**b**); and measuring thickness of spraying layer (**c**).

2.2.2. Tests of Pumpability and Shootability

Tests of pumping and spraying concrete were conducted at a shotcreting site in the simulated roadway in Wit Laboratory Mine Equipment Co., Ltd (Jining, China). The wet-mix shotcreting equipment (Model: SPB7-T) featured a high capacity of 7 m^3/h with the maximum aggregate size to reach 10 mm. The shotcreting equipment used is shown in Figure 6. The mixing procedure was as follows: dry materials (cement, silica fume, fine and coarse aggregate) were mixed for 1 min and then water and fibers were added during the additional 2 min of mixing. Shortly after mixing, samples were taken and the fresh properties of initial slump and mechanics properties were tested.

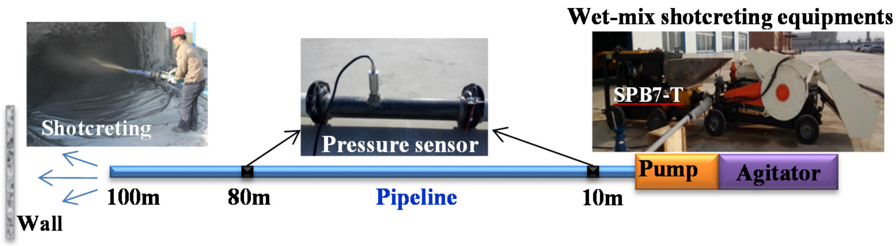

Figure 6. System of wet-mix shotcrete including pressure sensors.

The pumpability can be expressed indirectly by slump and pipe pressure drop measured, respectively, measured by slump cone and pressure sensors. The shootability can be indicated by rebound rate and the build-up thickness of once shotcrete. The larger slump and smaller pressure drop indicate the better pumpability. Lower rebound rate and thicker build-up thickness mean the better shootability. In the process of rebound tests, a plastic film was laying on the bottom of the wall. Next, a certain quantity of concrete was sprayed onto the wall and the rebound material was collected, weighted, and calculated after spraying. The rebound rate can be calculated as follows:

$$\text{Rebound rate} = \frac{W_r}{W_t} \times 100\%$$

where W_r is the weight of the material that rebounded g; and W_t is the total weight of the material sprayed g.

The build-up thickness was evaluated by spraying concrete mixture onto a vertical wall with a 0.4–0.5 MPa air pressure for 80 s by moving up and down the nozzle slightly. Figure 5c shows the typical shooting process and the build-up thickness measurement. All tests were carried out as per Chinese standard GB8076-2008 [53] and GB50086-2001 [44]. The systems of wet-mix shotcrete and pressure sensors are shown in Figure 6.

3. Experimental Analysis

3.1. First Series of Tests

First, fresh concrete was cast in the conventional manner for evaluating if the mechanical properties can meet the requirement for mine supporting, and then sprayed with wet-mix process for exploring its pumpability and shootability when crushed walnut shell was mixed in concrete as replacement aggregate. Mix proportion in the initial series is shown in Table 1. Four group mixtures were prepared with crushed walnut shell as coarse aggregate replacement of 25%, 50% and 75% percentage.

Table 1. Mix proportion with crushed walnut shell in the first series.

No.	RC (%)	Cement (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	CA (kg/m^3)		AEA (kg/m^3)
						Gravel	Walnut	
W0	0	410	40	198	909	665	-	0.067
W1	25	410	40	198	910	499	63.99	0.067
W2	50	410	40	198	908	333	127.98	0.067
W3	75	410	40	198	910	167	191.97	0.067

RC: replacement percentage of coarse aggregate; SF: silica fume; CA: coarse aggregate; AEA: air entraining agent.

3.2. Results of the First Series of Tests

3.2.1. Mechanical Properties

In the first phase, only preliminary tests were conducted to check if the idea of using crushed walnut shells to replace partial nature coarse aggregates could give good results. With this aim, only compressive and splitting tensile strength tests of casting concrete with different dosage of walnut shells were conducted, not including the mechanical properties of shotcrete. It was found in Figure 7 that the introduction of crushed walnut shell in the concrete in place of partial coarse aggregate caused a marked reduction in both of compression and splitting resistance. With increase of walnut shell, compressive and splitting tensile strength of concrete approximately linearly decreased. Compared with plain concrete (W0), the specimens W1, W2 and W3 with 25%, 50% and 75% replacement had the reduction of 28.7%, 41.9% and 63.6% in compression, as well as 28%, 47.93% and 68.8% in splitting tensile strength, respectively. Obviously, the reduction of splitting was relatively larger than uniaxial compression.

According the supporting requirement in terms of physical properties from Chinese Specifications for Bolt-shotcrete Support [44] and related studies [54–57], more than 20 MPa of compressive and 2.5 MPa of splitting tensile strength is acceptable in coal mine support. Therefore, only W0 and W1 can achieve these requirements, as shown in Figure 7. For this reason, other concretes with more walnut shell could be used unless relative remedial measures were done, such as adding fiber to enhance the splitting tensile strength [38,40,49,58,59].

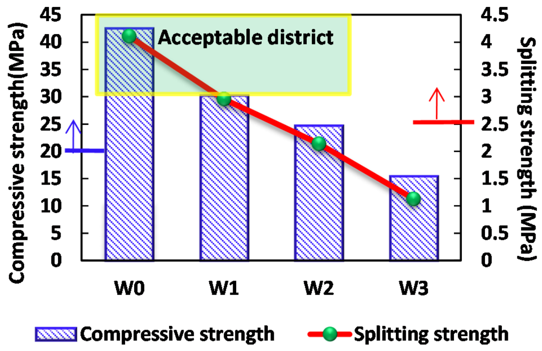

Figure 7. Mechanical properties of casting concrete with crushed walnut shell.

3.2.2. Density and Compressive Strength Relationship

Khankhaje et al. [11] found that the fresh density was slightly higher than the hardened density and both showed a good relationship to each other. The difference of density between cast and sprayed mixes was not significant, except for few extreme cases [60]. Hence, in this article, fresh density of casting concrete with crushed walnut shell was recorded. It can be seen in Figure 8 that the average fresh density values ranged from 1850 to 2150 kg/m^3. According to the specification from ACI [61] and ASTM [62], the density of structural lightweight concrete should be less than 2000 kg/m^3. In addition, lightweight concrete is classified with a density ranging from 1314 kg/m^3 to 1777 kg/m^3 [11]. Thus, the range of density of specimens in these tests was close to the requirement of lightweight concrete.

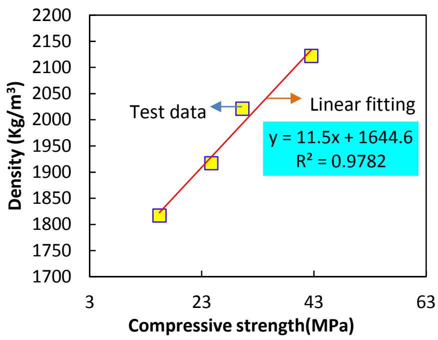

Figure 8. Relationship between density and compressive strength.

The compressive strength of concrete depends on density as one of the most important variables to consider in the design of concrete structures [63]. The relationship between compressive strength and density of concrete mixtures is plotted in Figure 8. A linear relationship between density and compressive strength can be observed in Equation (1), which obtained a coefficient of determination, R^2, of 0.9782 for all specimens, and thus indicated high confidence for the relationship.

$$y = 11.5x + 1644.6 \quad (1)$$

where y is density (kg/m^3) and x is the compressive strength (MPa) of casting concrete mixture.

3.2.3. Pumpability and Shootability

As usual, slump test is the standard test for the workability of fresh concrete, which measures the consistency according to ACI 116R [61]. Mannan and Ganapathy [64] found the low slump (0–4 mm) showed a very low workability. However, it does not necessarily mean that low slump ensures less pumpability. To determine the pumpability of fresh concrete after adding crushed walnut shell, pressure drop per meter was measured in tests with pressure sensors. It can be seen in Figure 9a that slump declined slightly with increasing walnut shell replacement while the pressure drop also decreased from 0% to 75% (except point W3), which was expected because aggregates mixed with walnut shells are likely to cluster closely due to the thin walnut shells instead of some approximately spherical particles. Because thin shell with convex and concave portions is easily generating the framework of aggregates, also called aggregate interlock characteristic due to angular and rough edges of crushed shell [65], to resist the flow, then reduce the slump in Figure 10 (SW), and appropriate framework of aggregates can avoid separation at the same time improving flow of concrete with low pressure drop per meter in Figure 10 (FW) under the primeval condition of lubrication layer near inner pipe has been formed [66]. As shown in Figure 10, $h_2 > h_1$ means adding crushed walnut shell or fibers decreased the slump. $l_2 > l_1$ means the thickness of lubrication layer formed as pumping plain concrete (F0) was thinner than that of pumping mixtures with walnut shell (FW) or fibers (FF) because the situation that more coarse aggregates in Figure 10 (F0) is prone to dispersion near inner pipe wall effects the formation of lubrication layer while coarse aggregates in Figure 10 (FW) were likely to gather in the center of pipes with the interlock effect. However, too much walnut shell, causing too tight mixture and easily breaking lubrication layer in pipes, might produce huge resistance along with high pressure drop, which was the interpretation of outlier W3 in term of high pressure drop.

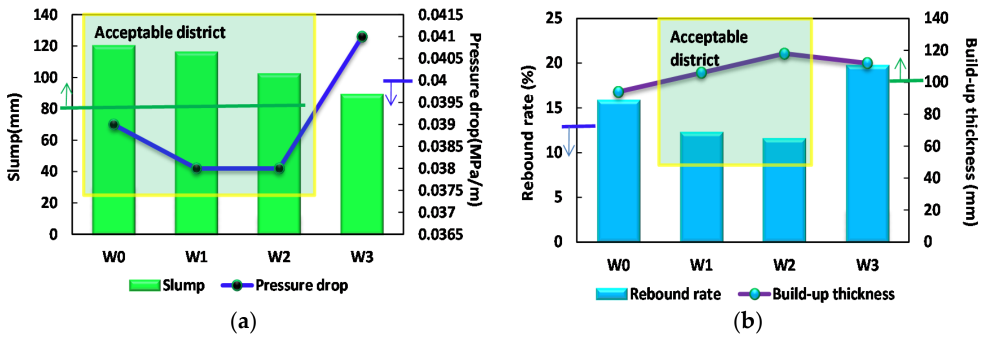

Figure 9. Pumpability (**a**); and shootability (**b**) of fresh concrete with crushed walnut shell.

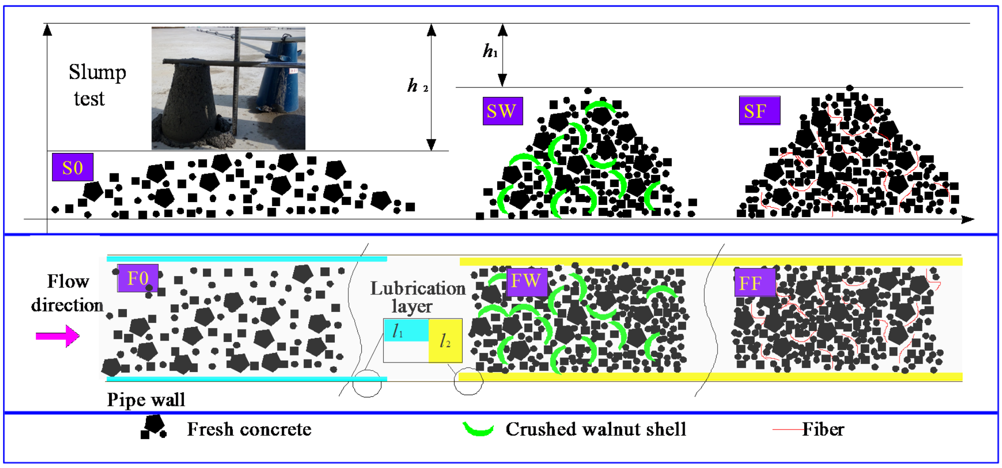

Figure 10. The aggregate interlock or framework with crushed walnut shell or fibers in terms of slump or pipage tests. S: slump test; F: pipage test; *h*: slump height; *l*: thickness of lubrication layer; S0 and F0: plain concrete; SW and FW: concrete with walnut shell; SF and FF: concrete with fiber.

Figure 9b indicates that rebound rate declined with increasing lightweight walnut shell from 0% to 50%, which is similar to the results in [60], and the build-up thickness changed in small range with fluctuating at 100 mm. Therein, W3 was an outlier with the largest rebound rate of about 20%. It also can be seen (Figure 11) in site that the rebound aggregates were very obvious during W3 test, and the divergent angle of spraying W3 (α_1) is larger than that of W2 (α_2) because more lightweight walnut shell mixed in W3 mixture was easily blew out from the spraying stream.

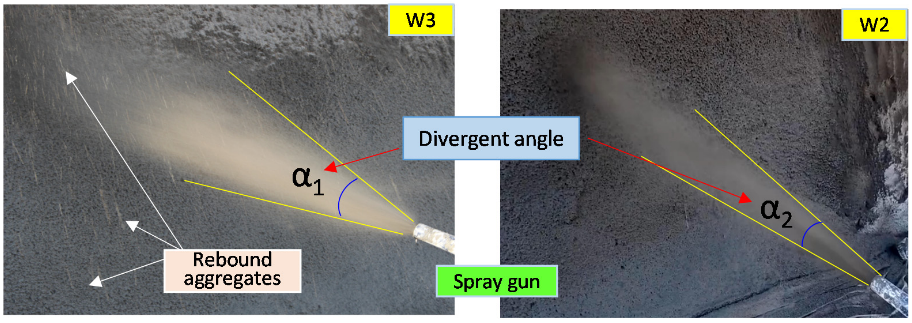

Figure 11. Comparison of rebound and divergent angle between W3 and W2.

According to the literature [54,55,67], more than 100 mm of slump and build-up thickness, lower than 0.04 MPa/m of pressure drop and 13% rebound rate, respectively, are more likely available in terms of pumpability and shootability. In order to guarantee the extent of lightweight concrete, another concrete mixture with 35% aggregate replacement of walnut shell was chosen but the splitting tensile strength should be enhanced. Hence, in the next series, fibers were mixed in concrete to reduce cracks and improve its splitting tensile strength.

3.3. Second Series of Tests

Because of the results gained from the above tests, it was considered appropriate to further investigation with improving splitting tensile strength by adding fiber. With this aim, specimens were cast and sprayed using the wet-mix process and the resulting four mixes were designated, PP, PET, and PET + PP, respectively, and the mix proportions are shown in Table 2. In order to analyze the effect of PET fiber on shotcrete clearly, the polypropylene (PP) fiber was added to compare the results and the mechanical tests of concrete after spraying were supplemented.

Table 2. Mix proportion with walnut shell and fibers in the second series.

No.	**Length (mm)**	**Cement (kg/m^3)**	**SF (kg/m^3)**	**Water (kg/m^3)**	**Sand (kg/m^3)**	**CA (kg/m^3)**		**AEA (kg/m^3)**	**Fiber (kg/m^3)**
						Gravel	**Walnut**		
Blank	-	410	40	198	908	432.3	167	0.067	
PP	30	410	40	198	908	432.3	167	0.067	0.9
PET	30	410	40	198	908	432.3	167	0.067	6.5
PET + PP	30 + 15	410	40	198	908	432.3	167	0.067	0.45 + 3.25

SF: silica fume; CA: coarse aggregate; Blank: the blank group; AEA: air entraining agent; PP: specimens with polypropylene fiber; PET: specimens with PET fiber; PET + PP: specimens with PET fiber and polypropylene fiber.

3.4. Results of the Second Series of Tests

3.4.1. Results of Compressive and Splitting Tensile Strength

The charts in Figure 12 show that concrete reinforced with different fibers gave the most satisfactory results for the splitting tensile strength of the concrete mixtures. With mixing fibers, splitting tensile strength of casting concrete (CSS) and shotcrete (SSS) achieved about 40% improvement compared with blank specimens. The range of tensile strength of mixtures with fiber was from 3.5 MPa to 4.3 MPa. This was a desirable result that concrete with more ductile behavior can be obtained by mixing PET or PP fibers.

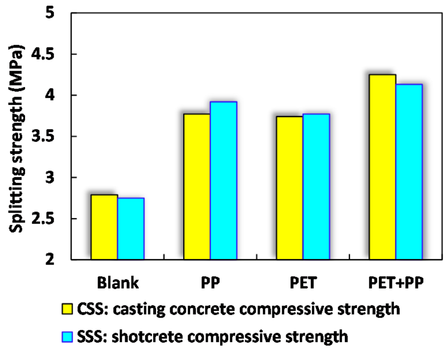

Figure 12. Comparation between (casting concrete) CCS and (shotcrete) SCS.

However, the influence of fiber, PET or PP, on the tensile strength seemed to be inverse to that of the compressive strength of the samples. For example, single adding fiber reduced the compressive strength of casting concrete (CCS) and shotcrete (SCS) such as specimens of PP and PET shown in Figure 13. It might be because during concrete curing the high water absorption of walnut shell as aggregate replacement changed the water-binder ratio of concrete mixture that acted a key controlling factor in compression. Moreover, the poor bond between cement pastes with fibers may lead to the reduction in compressive strength. The other reason reported was that the hollow side of shell was difficult to fill with cement paste whereas the amount of cement paste in concrete is limited [11]. Furthermore, the compressive and splitting tensile strength of shotcrete mixture seemed to be higher than that of casting concrete, which may be caused by the compacted effect of spraying force [68]. Wherein the specimens (PP + PET) combined with two types of fibers had the interesting results of maximal value in terms of compression and splitting tensile strength in casting concrete or shotcrete.

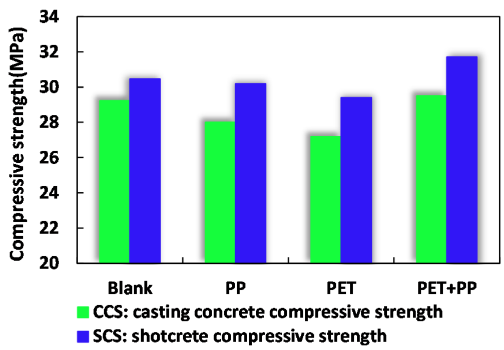

Figure 13. Comparation between CSS and SSS.

In the early tests, PP fiber with length of 30 mm mixed in concrete was prone to be twined together, which may cause strength loss, especially for compression. Thus, 15 mm length fiber was next mixed into mixture compounded with PET fiber (PET + PP). From the analysis, it was possible to assert that tests had confirmed the better behavior of multi-dimensions fiber than the single-mixture one and, in addition, the advantage of enhancing splitting tensile strength was much better than compressive strength after mixing fibers. The results that compressive strength became poor with mixing PP fiber concrete but splitting tensile strength improved are repeatedly reported in many studies [69–71], and multi-dimensions fiber reinforcement concrete can enhance the mechanical properties due to compounding effect of different fibers [39,42,69].

3.4.2. Results of Pumpability and Shootability

Figure 14 shows that adding fibers, PP or PET, reduced slump while also decreasing pressure drop per meter. In comparison to the blank mixture, 18.6%, 8.6% and 16% decrease in slump was observed for the PP, PET and PP + PET mix designs, respectively. As usual, the low slump is not beneficial for concrete flowing in pipes that generally increases the pressure drop. According to analysis, slump loss caused by mixing fibers is not identical to ones produced by less water or chemical admixture. Because fibers can cluster mixture to enhance the stability of fresh concrete in terms of reducing bleeding or segregation, such as mixing the thin shell of walnut. A new framework was formed with the intertexture of fibers or walnut shell, as shown in Figure 10 (SF and FF), which is also the reason fibers improved the shootability in terms of reducing rebound rate and increasing build-up thickness (Figure 15). For this reason, when it comes to pipe flow, with the formation of that thicker lubricant layer in the vicinity of pipe wall, stable concrete plug, due to the clustering effect of fibers, flows readily in pipes with lower pressure drop shown in Figure 10 (FF). When referring to shotcreting, concrete sprayed on the surface of walls becomes less flowable and more viscous because of fiber framework clustering discrete aggregates. The rebound rate of PET mixture was lower than that of PP mixture, which can be explained by the report that both density and flexural rigidity of different fiber influence rebound and the heavier fiber is more likely to reduce rebound [72]. In addition, PP mixture had more contribution on pumpability compared with other mixture, thus, the lowest pressure drop was achieved with the minimal slump. Shotcrete with PET had the lowest rebound rate but the best build-up thickness belonged to one with multi-scale fibers (PET + PP).

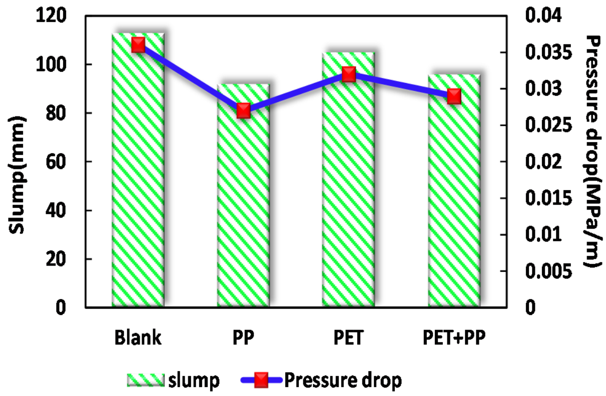

Figure 14. Effect of fibers on pumpability.

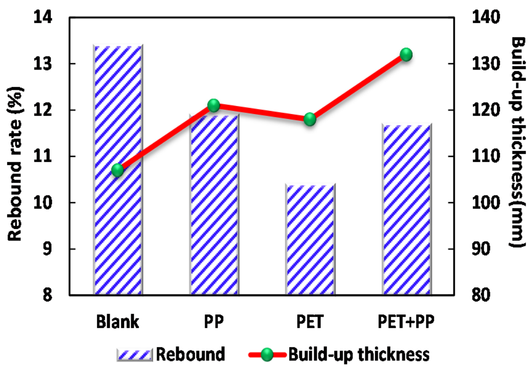

Figure 15. Effect of fibers on shootability.

3.5. Relevant Discussion

3.5.1. Compressive and Splitting Tensile Strength Relationship

The relationship between compressive and splitting tensile strength in this study was plotted (Figure 16). At the same compressive strength, the splitting tensile strength of specimens with fiber (including PET and PP fiber) in this study was higher than that of plain concrete mixture (PC).

The splitting tensile strength of fiber casting concrete with walnut shell (FC) was the highest in the same rank comparison and fiber shotcrete with walnut shell (FS) fell into the medium value. It might be because partial fibers, PET or PP, were lost by rebound during the process of spraying, which induced slight reduction in splitting tensile strength when compared with FC.

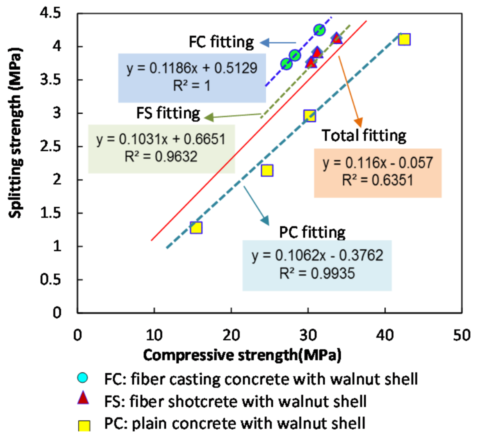

Figure 16. Relation between compressive strength and splitting tensile strength.

As shown in Figure 16, the splitting tensile strength was also proportional to the compressive strength. Linear relationships between splitting and compressive strength of FC, FS, PC and total specimens can be observed in Equations (2)–(5), which obtained a coefficient of determination, R^2, of 1, 0.96, 0.99, and 0.64 for the specimens, respectively, and thus indicated high confidence for the relationship for the same type of specimens.

$$y = 0.1186x + 0.5129 \quad (2)$$

$$y = 0.1031x + 0.6651 \quad (3)$$

$$y = 0.1062x - 0.3762 \quad (4)$$

$$y = 0.116x - 0.057 \quad (5)$$

where y is splitting tensile strength (MPa) and x is compressive strength (MPa).

The relationship between compressive and splitting tensile strength in this study was also compared with that of shotcrete without aggregate replacement [73] (Figure 17). It can be seen that the influence of fiber on the approximately linear relationship between splitting and compressive strength is not obvious, i.e. all data including fiber or plain shotcrete approached the fitting line closely in Figure 17, which was different from the results of our study (Figure 15) on PP or PET fiber according to the relative larger difference of intercept and slope of fitting lines. However, as a whole, the relationship between compressive and splitting tensile strength was same for both. According to analysis, the difference between Figures 16 and 17 was from the fiber type; additionally, it might be caused by the irregular shape of walnut shell as aggregate replacement that was one of the factors for controlling strength [63,74].

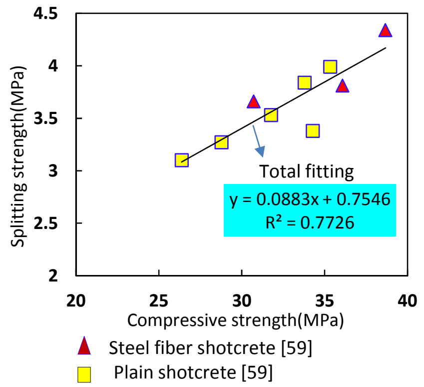

Figure 17. The relationship between compressive and splitting tensile strength of shotcrete without aggregate replacement.

3.5.2. Relationship: Rebound–Density and Rebound–Build-Up Thickness

The rebound rate was correlated with the density of mixture in Figure 18. The rebound rate increased with an increase in density, excepting the outlier that is mixture W3 in Table 1. As the normal trend, a similar linear relationship was plotted in Equation (6) with a good coefficient of determination, R^2 of 0.8954. The result was similar to an earlier study on the influence of particle density on rebound that revealed that a lower density was beneficial for reducing rebound [60,72].

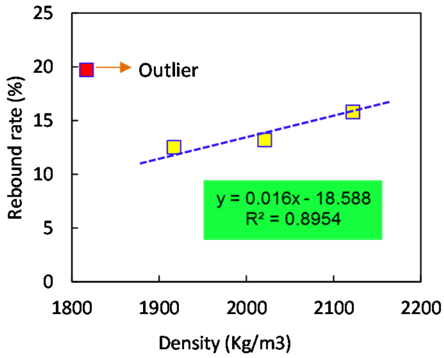

Figure 18. Relation of rebound and density.

Armelin and Banthia [75] illustrated the tendency for a particle to rebound was related to a tradeoff between its ability to indent the substrate and its susceptibility to ejection. A lightweight aggregate was more likely to resist ejection when reaching the wall sprayed [72].

Therefore, some crushed walnut shell as light aggregate may not even be able to reach the substrate but rather be fanned out from the stream. This was why outlier appeared in W3, owning the highest rebound and smallest density, with higher percentage of walnut shell than other mixtures. The reason also explained the larger divergent angle of spraying W3 in Figure 10.

$$y = 0.016x - 18.588 \quad (6)$$

where y is rebound rate (%) and x is density (kg/m^3).

A linear relationship between the rebound rate and build-up thickness is also shown in Figure 19 with Equation (7), excepting outlier of W3.

$$y = -0.1145x + 25.731 \quad (7)$$

where y is rebound rate (%) and x is build-up thickness (mm).

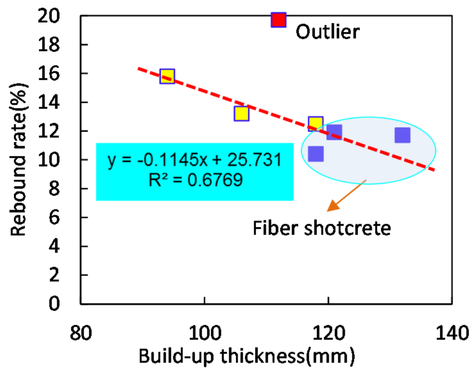

Figure 19. Relation of rebound and build-up thickness.

As reported in the literature [76], the build-up thickness presented an inverse correlation with rebound rate. It also can be seen that adding fibers is beneficial to shootability of fresh concrete, along with low rebound and high build-up thickness. Figure 19 shows that the build-up thickness increased from 90 to 140 mm when the rebound rate declined by about 30%. These results indicated that crushed walnut shell could be used to replace partial natural coarse gravel for attempting to produce lightweight shotcrete with acceptable mechanical characteristic, pumpability and shootability. Furthermore, PET fiber made from waste plastic bottles was mixed into fresh concrete to enhance its splitting tensile strength, also improving the pumpability and shootability of concrete mixture, but slightly reduced its compressive strength. According to Chinese standard [44], PET fiber wet-mix shotcrete with crushed walnut shell of about 35% coarse aggregate replacement could be used for roadway support as lightweight shotcrete.

4. Conclusions

The utilization of crushed walnut shell as lightweight coarse aggregate to attempt to produce lightweight wet-mix shotcrete was proposed and tested in this study. The mechanical, pumpability and shootability behaviors of wet-mix shotcrete with walnut shell were tested and discussed. In order to optimizing its properties, PET fiber was used as reinforcement element, and the behavior of PET fiber shotcrete was compared with conventional shotcrete. Based on the above experiments, the following conclusions were made:

(1) In this study, walnut shell was crushed with irregular shaped (polygonal or flaky) with 1–4 mm thickness. They were sieved into one size category, 5 mm to 10 mm. The surfaces of convex portion of crushed shell are relatively smooth, compared to rough surfaces of the concave side along the cracked edges. The specific gravity of walnut shell is obviously lower than that of the natural aggregate. Hence, walnut shell can be termed as lightweight aggregate as it has low specific gravity.

(2) In the preliminary tests, compressive and splitting tensile strength of casting concrete with different dosage walnut shell were conducted. With increase of walnut shell, compressive and splitting tensile strength of concrete decreased. Compared with plain concrete (W0), the specimens W1, W2 and W3 with 25%, 50% and 75% replacement had the reduction of 28.7%, 41.9% and 63.6% in compression, as well as 28%, 47.93% and 68.8% in splitting tensile strength, respectively. Furthermore, a linear relationship between density and compressive strength was obtained with a good coefficient of determination, R^2 of 0.9782.

(3) In order to determine the pumpability of fresh concrete after adding walnut shell, pressure drop per meter was measured in tests. Slump and pressure drop declined slightly with increasing walnut shell replacement from 0% to 75%. Mixing aggregates with walnut shell were likely to cluster closely due to interlock characteristic of crushed walnut shell with angular and rough edges, which was beneficial for reducing separation and improving flowability of fresh concrete.

Additionally, appropriate dosage of walnut shell (W1 and W2) can improve the shootability of fresh concrete with low rebound rate and larger build-up thickness.

(4) With mixing PET and PP fiber, splitting tensile strength of casting concrete (CSS) and shotcrete (SSS) had achieved about 40% improvement compared with blank specimens. However, adding fibers, PET or PP, caused the loss of the compressive strength of the samples. Wherein, the specimens (PP + PET) with two types of fiber had the interesting results of maximal value in terms of compression and splitting strength of casting concrete or shotcrete. Adding fibers reduced slump and flowability of fresh concrete. In addition, fibers improved the shootability in terms of reducing rebound rate and increasing build-up thickness.

(5) A linear relationship between splitting and compressive strength of FC, FS, PC and total specimens was plotted with a coefficient of determination, R^2, of 1, 0.96, 0.99, and 0.64, respectively. In addition, the relations of rebound, and density and build-up thickness were discussed. Wherein, the rebound rate increased with an increase in the density, except the outlier W3, and the build-up thickness presented an inverse correlation with rebound rate.

Acknowledgments: The authors would like to acknowledge the team of wet-mix shotcrete in College of Mining and Safety Engineering for the financial and technical support. They also appreciated Wit Laboratory Mine Equipment Co., Ltd. for the preparation and execution of shotcrete tests. This study was funded by such projects as National Natural Science Foundation of China (grant number 51404145); Shandong Natural Science Foundation of China (grant number ZR2013EEQ021); Applied Research Project Foundation of Qingdao Postdoctoral Researcher (grant number 2015176); Director Foundation of State Key Laboratory of Mining Disaster Prevention and Control Co-founded by Shandong Province in China (grant number MDPC2012ZR02); and Student innovation fund of College of Mining and Safety Engineering in SDUST (grant number KYKC17002).

Author Contributions: Weimin Cheng was involved in drafting the manuscript and revising it critically; Guoming Liu made substantial contributions to conception and design of the experiment and acquisition of data; and Lianjun Chen gave the final technological approval of the version to be published.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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