coatings

Article

Effect of Slurry Coating Modified Methods on Water Absorption of Recycled Coarse Aggregate

Lei Yu [1,*], Sizhong Lv [2], Zhijie Zhao [3] and Zhaolei Liu [3]

1 Research Institute of Highway Ministry of Transport, Beijing 100088, China
2 Shandong Highway Incorporated Company, Beijing 250014, China; sdgslsz@126.com
3 Beijing Xinqiao Technology Development Co., Ltd., Beijing 100088, China; zj.zhao@rioh.cn (Z.Z.); 13910147210@139.com (Z.L.)
* Correspondence: yuleimabel@163.com; Tel.: +86-134-3694-8400

Abstract: Water absorption rate of the recycled coarse aggregate is higher than the natural ones. Until now, there is no test method to record the instantaneous value of the water absorption although this could help us to understand the recycled coarse aggregate better. This paper developed a new device that can record the water absorption continuously and calculate the water absorption rate automatically. The water absorption curve from 0 min to 60 min can be plotted smoothly. The performances of modified recycled coarse aggregate and concretes with recycled coarse aggregate have also been studied. The result shows that the water absorption rate increases fast and about 90% water has been absorbed during the first 10 min. The slurry of silicon nitride with 500 nm particle size can reduce the 10 min water absorption rate of the recycled coarse aggregate from above 4.5% to below 2.5%. A recycled coarse aggregate wrapped with wet slurry is better than the ones wrapped with dry slurry shell for the slump of concrete. Compared to the concrete without any recycled coarse aggregate, the compressive strength and the splitting tensile strength of the concrete with recycled coarse aggregate modified by fresh cement slurry have been increased by more than 20%.

Keywords: recycled coarse aggregate; water absorption; silicon nitride; modified method

Citation: Yu, L.; Lv, S.; Zhao, Z.; Liu, Z. Effect of Slurry Coating Modified Methods on Water Absorption of Recycled Coarse Aggregate. *Coatings* **2022**, *12*, 363. https://doi.org/10.3390/coatings12030363

Academic Editors: Junjie Wang and Hongwei Lin

Received: 8 February 2022
Accepted: 6 March 2022
Published: 9 March 2022

1. Introduction

In the reconstruction and extension project of highway, there are concrete structures, such as bridges, the concrete pavement, retaining walls and curbs that need to be torn down. So, a lot of old concrete materials need to be dealt with. If thrown away, they will occupy a quite large field area. Not only will it lead to the waste of resources, but also cause environmental problems. Nowadays, the best way to deal with them is to take advantage of them. Crushing them into coarse aggregate and recycling them into the project would be a good way. Some countries, such as Germany, Japan, Denmark and Korea, have drafted technical regulations to normalize the recycling of concrete [1].

However, the recycled aggregate still has some problems that need to be modified. One is that quite a large amount of mortar sticks to the aggregate. It will cause high water absorption during the mixing process and then lead to the slump of the concrete, decreasing swiftly and obviously [2–5]. Generally, the strength of the recycled coarse aggregates is not as strong as the normal aggregate. It may cause the concrete to have low compressive strength [6–11].

Nowadays, there are two kinds of methods to modify the recycled coarse aggregate. One is breaking the mortar and normal aggregate into two parts. The other one is blocking the pores of the mortar on the aggregate. For the former method, there are three means to achieve this result. One is baking them with a heating device [12,13]. The second is to grind them [14–16]. The third is to steep them with an acid, such as hydrochloric acid [17].

For the method of pore blocking, nanometer materials filling, silicone agent, carbon dioxide curing, mineral admixture slurry wrapped are all efficient methods to block the pores of the mortar on the recycled aggregate [18–22]. Jianhe Xie shows that the pozzolan slurry soaking methods can generally help to strengthen the weak adhered mortar. Forty percent fly ash and silica fume and 3% nano silica fume slurries with 4 h soaking time exhibited a comparable improving performance [23]. Some chemical materials, such as sodium bicarbonate and sodium carbonate, can react with the aqueous calcium hydroxide in the pore of the mortar. The carbonate products often are solid so that they can fill the pore of the mortar [24,25]. The effects of recycled aggregate on the performance of the concrete are also studied. Hailong Wang shows that the permeability of recycled aggregate concrete is much lower than that of the concrete without recycled aggregate due to the on-going hydration and the pozzolanic reaction provided by the phosphorous slag and ground granulated blast-furnace slag additives in the recycled aggregate concrete mixture [26]. Jianhe Xie studied the compressive and flexural behaviours of recycled aggregate concrete modified with silica fume and fibers. The result shows that the coupling effect of silica fume and steel fiber was better than that of the silica fume and polypropylene fibres [27]. Most of the treatments are currently being examined on a small scale under laboratory conditions. How these techniques can be applied to large scale commercial production requires further research and investigation [28].

Considering carbon emission, baking and heating methods will cost a lot of energy. For the acid steeping method, not only will it dissolve the mortar on the aggregate, but also it will cause erosion for the normal aggregate. For the highway construction, the crushed concrete is a kind of waste, and the quantity is very large. Considering the construction cost and convenience, wrapping the admixture slurry outside the aggregate and immersing the aggregate into the silicone agent are two different considerable methods.

The purpose of this paper is to investigate the timely water absorption of the recycled aggregate during 0–60 min and find a properly modified method for decreasing the water absorption of the recycled coarse aggregate. Although the reference shows a newer method to test the water absorption of the recycled coarse aggregate, the data collected are still not continuous [29,30]. Since there is no method to test the timely water absorption of the aggregate before, a new method has to be invented in this paper. The size of the particle can affect the amount of its slurry absorbed by the recycled coarse aggregate [31]. The wave method and soaking the aggregate in acid are not all convenient methods for field construction [32]. Considering the particle size in the slurry and the construction convenience, the slurry made by cement, silica fume, silicon nitride is used for wrapping the recycled aggregate to decrease the 0–60 min water absorption of the recycled coarse aggregate. To know the effect of the modified recycled aggregate on the concrete, the concretes with recycled coarse aggregate wrapped by wet slurry or by dry slurry shell are made to distinguish the slump and mechanical performance. By testing the slump and mechanical performance of the concrete with modified recycled coarse aggregate, the effects of the modified method to the concrete can be clear. To save cost for construction, the mixing way of the aggregate modified by cement slurry is selected by contrast experiment. Finally, this paper tries to find a mixing method with a high performance to cost ratio for the mixing progress during construction.

2. Materials and Methods

2.1. Materials

2.1.1. Recycled Coarse Aggregate

In order to obtain the common rules of the water absorption of recycled coarse aggregate, two different origin recycled coarse aggregates are prepared. One is from the slabs of the bridges of a highway which is located in Jinan City, Shandong province, China. The compressive strength range of the concrete from these bridges is from 5800 psi to 7250 psi. The other is from the cement concrete pavements located in the same area. The compressive strength range of the concrete from the cement concrete pavements is from 4350 psi to 5800 psi. The aggregate from the bridges is numbered 1# and the one from the cement concrete pavement is numbered 2#. Both 1# and 2# include two particle sizes. They are

5–10 mm and 10–20 mm. The properties of these two kinds of aggregates are listed in Table 1. The apparent density and the 24 h water absorption are tested based on the ASTM C127-2015 [33]. The crushing value of the aggregate is tested based on the Chinese national standard, for which the number is GB/T 14685-2011 [34]. The chlorine ion content is tested based on the Chinese national standard, for which the number is JGJ/T 322-2013 [35].

Table 1. Properties of the aggregates.

ID	Range of Particle Size (mm)	Apparent Density (kg/m^3)	Crushing Value (%)	24 h Water Absorption (%)	Chlorine Ion Content (%)
1#	5–10	2671	21.5	6.11	0.0475
	10–20	2676		5.34	
2#	5–10	2689	29.5	6.83	0.0037
	10–20	2687		5.17	

2.1.2. Materials for Mixing Slurry to Modify the Recycled Aggregate

Four kinds of materials are used for modifying the water absorption of the aggregate by coating them. They are cement (C), silica fume (Si), nanometer silicon nitride (SiN) and silicone hydrophobic agent (SiH-agent). About the silica fume, there are two different diameter particles of 150 nm and 300 nm. The material ID can be defined as Si-150 nm, Si-300 nm. For the nanometer silicon nitride, there are also two kinds of particles such as 20 nm and 500 nm. The material IDs can be defined as SiN-20 nm, SiN-500 nm. The properties of the cement, silica fume and silicon nitride are listed in Table 2. The density and the specific surface area are tested separately based on the standard of ASTM C188-2009 and ASTM C204-2016 [36,37]. The properties of the silicone hydrophobic agent are listed in Table 3. The specification of the silicone hydrophobic agent is shown in the link [38]. Hydroxy Propyl Methyl Cellulose is used to increase the consistency of the slurry. The properties of the cellulose are listed in Table 4. The specification of the cellulose is shown in the link [39].

Table 2. Properties of the cement, silica fume and silicon nitride.

ID	Particle Size	Density (kg/m^3)	Specific Surface Area (m^2/kg)
C	/	3100	370
Si-150 nm	150 nm	300	28,000
Si-300 nm	300 nm	700	20,000
SiN-20 nm	20 nm	90	90,000
SiN-500 nm	500 nm	230	35,000

Table 3. Properties of the silicone hydrophobic agent.

Style	PH Value	Solid Content (%)	Density (kg/m^3)	Recommended Mixing Amount (%) of Cement Mass
FS-170	7.0	20	1015	1

Table 4. Properties of the cellulose.

Style	Fineness (μm)	Density (kg/m^3)	Color
GLHPMC01	150	500	white

2.1.3. Common Materials for Concrete

Commercial cement (grade 42.5) was used in the experiments. The properties of the cement are listed in Table 5. A polycarboxylate-based superplasticizer was used to guarantee that fresh concrete has a considerable slump. The mixing content is 1% of the cement amount. Natural sand was used as fine aggregate, and the measured value of the fineness modulus is 2.78. The cumulative screening percentage of the natural sand is listed in Table 6. Natural gravel with a particle size of (5–10) mm and (10–20) mm are used as normal coarse aggregate. The origin of the natural gravel is Shandong province in China. The 24 h water absorption, the crushing value and the apparent density of the normal coarse aggregate is 0.45%, 10.5% and 2730 kg/m^3, respectively. The properties of the cement are tested based on the Chinese standard GB 175-2020 [40]. The cumulative screening percentage of the natural sand is tested based on the Chinese standard GB/T 14684-2011 [41].

Table 5. The properties of cement.

Fineness (80 μm Square Hole Sieve) (%)	Water Requirement for Normal Consistency (%)	Setting Time (h: min)		Compressive Strength (MPa)		Splitting Tensile Strength (MPa)		Stability (Boil)
		Initial	Final	3 d	28 d	3 d	28 d	
3.1	27.6	2:59	3:59	29.8	49.9	6.7	9.3	qualified

Table 6. The cumulative screening percentage of the natural sand.

Sieve Size (mm)	4.75	2.36	1.18	0.6	0.3	0.15	0.075	<0.075
Cumulative screening percentage	11.62	32.2	43.58	55.6	79	93.3	99.9	100

2.2. Test Measurements

2.2.1. Water Absorption Measurements

A common method to detect the water absorption of the aggregate is soaking them in water and then dry them with a moist towel until the saturated surface reaches dry status according to ASTM C127-2015 [33]. The progress is obviously discontinuous. In order to obtain continuous data of the water absorption and plot the whole curve of the aggregate smoothly, I introduced a new method. The details of the measurement are shown as follows.

Take 5000 g coarse recycled aggregate and sieve them by the 4.75 mm sieve with square pores. Wash the rest of the coarse recycled aggregate and dry them by drying oven for 48 h. In order to avoid thermal decomposition in the mortar, set the drying oven temperature as 78 ± 3 °C instead of 105 ± 5 °C. Take the dry aggregate out of oven and static them cool down in the dryer with temperature 20 ± 2 °C. Quarter them and take out double sections. Weigh 1000 g aggregate from each section preparing for the next test. The water absorption testing apparatus is displayed in Figure 1.

First of all, put the net basket on the hook. Adjust the temperature of the water between 15 and 25 °C. Then, pour water into the overflow tank until the water begins flowing from the overflow port. Shut off the overflow port. Adjust the electronic hydrostatical balance to the number zero. Weigh m gram (m = 1000 ± 5 g) prepared dry coarse aggregate and put them into the net basket as soon as possible and not exceeding 30 s. Beat the net basket so that the air can expel from the net basket. Read the number of the 30th second on the balance as the initial quality of the coarse aggregate in water. Read the number of the 24th hour on the balance as the final quality of the coarse aggregate in water and denote it as m′. The principle of reading the number between the initial number and the final one is shown in Table 7. Considering the quick rate at which water absorption happens during the early stage, to draw a smooth curve, the frequency of reading the number in the early stage must be much higher than the late stage. The quality of the aggregate in water between the 30 s and 24 h is recorded as m″. After 24 h, take the coarse aggregate out of the water and dry them with a wet cotton cloth until the surface of the aggregate has no obvious water. Weigh them and record as m‴. The water absorption of the coarse aggregate can be calculated as Equation (1).

$$\omega = \frac{m'' + m''' - m' - m}{m} \times 100 \quad (1)$$

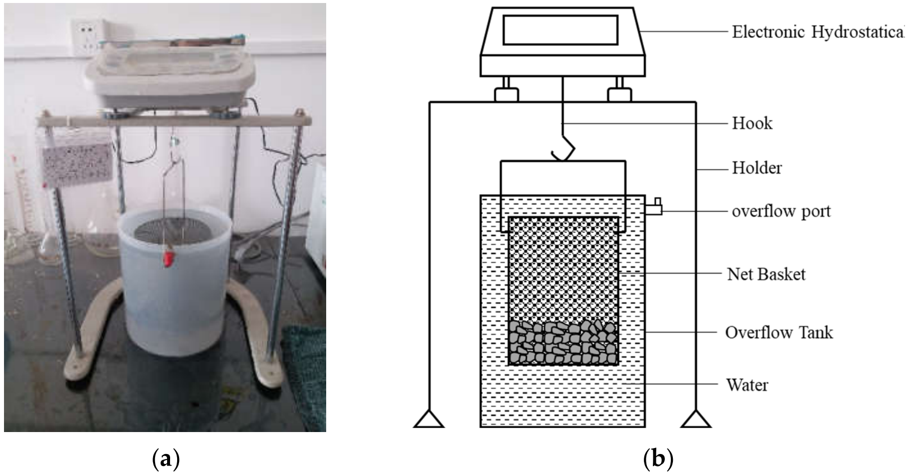


Figure 1. Water absorption testing apparatus: (**a**) Picture; (**b**) Schema.

Table 7. The principle for recording the number.

Test Time	30 s–10 min	10 min–20 min	20 min–60 min	30 min–1 h	1 h–6 h
Frequency of record number	30 s	1 min	5 min	10 min	1 h

2.2.2. Coarse Aggregate Modified

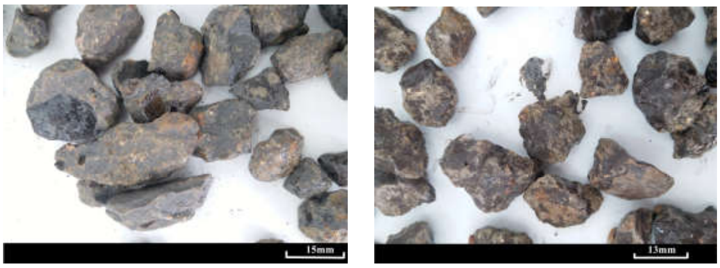
In order to wrap the coarse aggregate with the cement, silica fume and nanometer silicon nitride, the slurries of these powder have been made.

Reduce the aggregate by quartering the method to about 500 g and set aside into two parts. First of all, prepare the aggregate just like in Section 2.2.1. Then, put the cool, dry, prepared aggregate into the slurry, mix them until the particles are covered with slurry. Static the mixture for 2 h. For cement slurry, it should be stirred every 10 min to avoid congealing during the static time. After 2 h, sieve the mixture with the 2.36 mm sieve until that there is no obvious slurry dropping. Spread the aggregate on a pallet and carry them into the dry oven. The steps to dry the aggregate and the measurement of water absorption are the same as Section 2.2.1. The appearance of the aggregate covered with different materials is shown as Figure 2.

2.2.3. Performance Test of Concretes Made by the Recycled Coarse Aggregate

In order to distinguish the difference of aggregates modified by above methods, the concretes are prepared respectively by the modified aggregates above. The slumps of initial, 5 min, 10 min, 15 min have been tested according to ASTM C143/C143M-12 to observe the effects that the different aggregate modified methods have compacts on the concrete slumps [42]. The 28-d compress strength have also been tested according to ISO 4012-1978 [43] to verify that the modified methods cannot reduce the strength of the concrete.

(**a**)



(**b**)

(**c**)

(**d**)

Figure 2. The appearance of the aggregate wrapped with different material slurry: (**a**) Wrapped with cement slurry; (**b**) Wrapped with silica fume slurry (left: 150 nm, right: 300 nm); (**c**) Wrapped with silicon nitride slurry (left: 20 nm, right: 500 nm); (**d**) Wrapped with silicone hydrophobic agent.

2.2.4. The Mixing Procedure of the Concrete with the Dry Modified Aggregate and the Wet One

Considering concrete production in practical engineering, the mixing technology will be different between the dry modified aggregate and the wet one. If using dry modified aggregate, there may need to be a slurry pool at the construction site. First of all, prepare the slurry mixed by the modified material in the slurry pool, and then put the recycled coarse aggregate in the pool, wait for a certain time more than 1 h, fish out the aggregate, dry them under the natural sun or with other methods. Then, the dry modified recycled coarse aggregate can be used to make concrete.

If using the wet modified aggregate, the steps of treating the recycled coarse aggregate above can be simplified due to the dry step can be cut off.

2.2.5. Mixing Procedure of the Concrete with the Cement Slurry Wrapped Aggregate

There are two different mixing styles. One is preparing the wet modified aggregate with cement slurry as in Section 2.2.4. Then mix the prepared wet modified aggregate into the blender. The other method is mixing additional cement and water that the coarse aggregate wrapping needed firstly in the blender and then mixing all of the concrete raw materials including the recycled coarse aggregate and the normal coarse aggregate together at the same time. The contrast experiment of these two methods has been completed. In the contrast experiment, the 1# recycled coarse aggregates with (5–10) mm and (10–15) mm were used. The C-W group was made by the former method, but the C-T group was made by the latter method.

The quantity of the additional cement slurry which includes cement and water should be calculated with Equations (2) and (3), respectively.

$$m_{\mathrm{c}}^{\mathrm{C-T}} = (m_1\omega_1 + m_2\omega_2) \times \frac{m_{\mathrm{c}}}{m_{\mathrm{c}} + m_{\mathrm{w}}} \tag{2}$$

$$m_{\mathrm{w}}^{\mathrm{C-T}} = (m_1\omega_1 + m_2\omega_2) \times \frac{m_{\mathrm{w}}}{m_{\mathrm{c}} + m_{\mathrm{w}}} \tag{3}$$

In these two formulas, $m_{\mathrm{c}}^{\mathrm{C-T}}$—the extra cement quantity; $m_{\mathrm{w}}^{\mathrm{C-T}}$—the extra water quantity; m_1—the quantity of the unit recycled coarse aggregate with (5–10) mm; m_2—the quantity of the unit recycled coarse aggregate with (10–20) mm particle size; m_{c}—the quantity of cement in the original mix proportion; m_{w}—the quantity of water in the original mix proportion; the unit of all weight parameters is kilogram; ω_1—the water absorption of the recycled coarse aggregate with (5–10) mm particle size; ω_2—the water absorption of the recycled coarse aggregate with (10–20) mm particle size; the unit of the water absorption is %.

2.3. The Mix Proportion of Slurry and Concrete

2.3.1. The Mix Proportion of Slurry

The mix proportions of the slurry used for wrapping the recycled aggregate are listed in Table 8.

Table 8. The mix proportion of the different slurry (kg/m^3).

Cement	Silica Fume		Nanometer Silicon Nitride		Water	Cellulose
	150 nm	300 nm	20 nm	500 nm		
500	/	/	/	/	264	5
/	150	/	/	/	300	2
/	/	150	/	/	300	2
/	/	/	30	/	600	/
/	/	/	/	100	130	/

2.3.2. The Mix Proportion of Cement

According to the experiment design in Section 2.2.3 and calculation method in Section 2.2.5, a certain amount of normal coarse aggregate will be replaced by the 1# recycled coarse aggregate. The C30 concrete was made to test the slump and mechanical performance. The details of the mix proportions of concrete with different aggregates are listed in Table 9. Group None is the treatment group without any recycled coarse aggregate. Groups with D letter concretes include a half of recycled coarse aggregate covered with dry slurry shell. The serial number of groups with D letter will vary along with the different slurry shell, as shown in Table 9. For example, if the recycled coarse aggregate is covered with cement slurry shell, then it is numbered C-D (cement-dry). Relatively, Group W is on behalf of the concretes with the wet slurry wrapping on the recycled coarse aggregate.

The numbers will also vary along with the different wet slurry materials. For example, if the recycled coarse aggregate is covered with fresh cement slurry, then it can be numbered C-W (cement-wet). Group C-T has been introduced in Section 2.2.5.

Table 9. Mix proportions of concrete with different aggregates (kg/m^3).

No.	Cement	Water	Sand	Coarse Aggregate			
				(5–10) mm		(10–20) mm	
				Normal	Recycled	Normal	Recycled
None	332	175	860	420	0	632	0
C-D	332	175	860	210	210	316	316
C-W	313	165	860	210	222	316	333
C-T	351	185	860	210	210	316	316
Si-150 nm-D	332	175	860	210	210	316	316
Si-150 nm-W	332	175	860	210	210	316	316
SiN-20 nm-D	332	175	860	210	210	316	316
SiN-20 nm-W	332	175	860	210	210	316	316

From Table 9, C-D, C-W and C-T groups have different unit weights of materials; this is because the recycled coarse aggregate adsorbs fresh cement slurry. The fresh cement slurry will enhance the compressive strength of the concrete. It will lead to fuzziness of whether the compressive strength is due to the modified aggregate or the spare fresh cement slurry. So, the cement and the water from the fresh cement slurry which is absorbed by the recycled coarse aggregate must be deducted. The amount of the deducting weight of the cement and water are calculated by the formula 2 and 3 in Section 2.2.5. In a similar way, considering the comparability between group C-W and C-T, the group C-T has to add equal cement and water so that these two groups have the same water and cement ratio.

3. Results

3.1. Water Absorption of Recycled Coarse Aggregate

In order to obtain common rules for water absorption of recycled coarse aggregate, two different origin recycled coarse aggregates are prepared. The water absorption of these two kinds of recycled coarse aggregate from 0 min to 60 min are displayed in Figure 3.

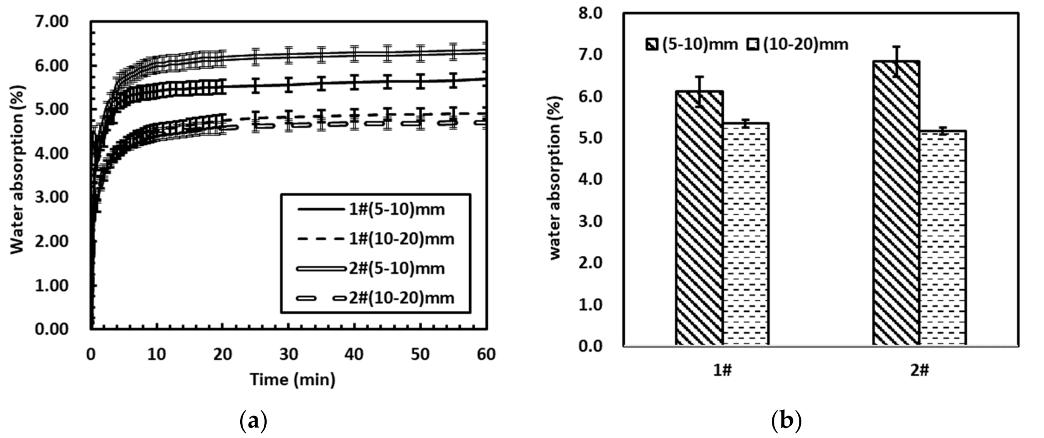


Figure 3. Water absorption of the different origin recycled coarse aggregates, (**a**) 0 min–60 min, (**b**) 24 h.

From Figure 3a, it can be seen that the curve tend of the two kinds of recycled coarse aggregates are almost the same as each other. During the first 10 min, water absorption is quick. After 10 min, the rate of the water absorption becomes smooth. For different recycled coarse aggregate, about 90% of water has been absorbed in the first 10 min. From Figure 3, it can also be seen that different origin recycled coarse aggregate may have different water absorption characteristics. The water absorption of the aggregate with (5–10) mm particle size is absolutely more than the one with (10–20) mm particle size. This may be because the content of mortar sticking on or mixing in the (5–10) mm particles is more than that sticking on the (10–20) mm aggregate. The mortar has stronger water absorption ability than the natural aggregate. The more content of mortar in the aggregate, the stronger water absorption ability it will have. From Figure 3b, it can be seen that the rule is the same as the 60th minute. No matter 1# or 2#, the water absorption of the (5–10) mm aggregate is larger than that of the (10–20) mm ones. The water absorption of 2# aggregate with (5–10) mm particle size is 6.83% which is a little bigger than the one of 1# aggregate which is 6.11. The opposite phenomenon, that 1# water absorption is a little bigger than 2# water absorption, appears with the (10–20) mm particles. Exploring the reason, it may be due to the different origin of the aggregates. The 1# comes from the slab of the bridge. The 2# comes from the pavement. In China, there is a common rule that the concrete grade of bridge slab is larger than that of the pavement. In general, the concrete grade range of the bridge slab can be C45-C50 but the one of pavement can be C25-C30. The number of pores is the main reason for the water absorption in the concrete. So, the water absorption of 2# with (10–20) mm particle size is larger than the one of 1#. Why does the water absorption in (5–10) mm have the opposite phenomenon? This may be because the content of mortar in 1# is more than that in 2#. Due to the mechanical disruption during production process, the mortar in the concrete is broken into small particles with (5–10) mm but not (10–20) mm. The bridge slab with higher strength, smaller water cement ratio and more cement content has more mortar than the concrete pavement with lower strength, higher water cement ratio and low cement content.

3.2. Water Absorption of Modified Recycled Coarse Aggregate

To find effective methods of modified recycled coarse aggregate so that reduce the water absorption, four kinds of materials are selected to mix them with water into slurry for wrapping the recycled coarse aggregate. Make the 1# aggregate as a representative. The water absorption of modified recycled coarse aggregates is displayed in Figure 4.

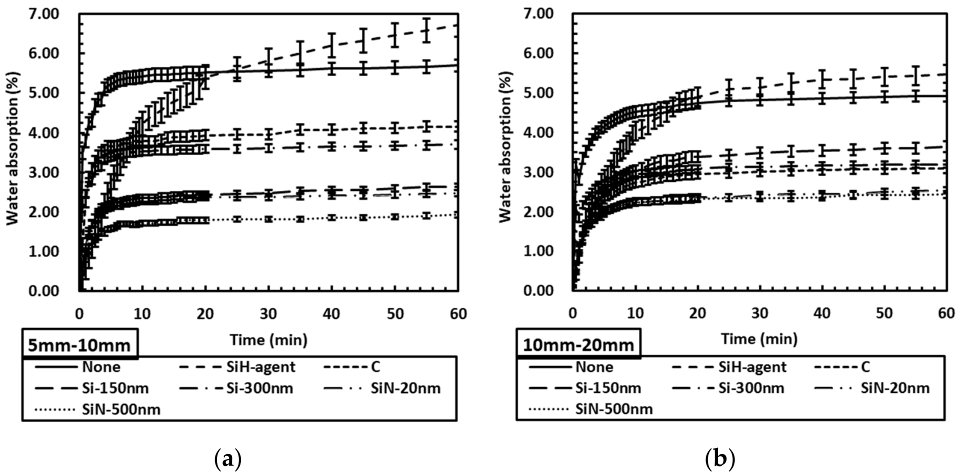


Figure 4. The water absorption of modified recycled coarse aggregate, (**a**) (5–10) mm, (**b**) (10–20) mm.

First, from Figure 4, after wrapping the slurry shell, no matter the (5–10) mm recycled coarse aggregate or the (10–20) mm ones, the (0–10) min water absorption of the recycled coarse aggregate is significantly reduced. Noteworthy, the SiH-agent can slow down the first 10 min water absorption rate of the recycled coarse aggregate and can prolong the sum of the first 10 min water absorption to 20 min. However, it can increase the sum water absorption at last. So, it may not be a good modified material. C, Si, SiN can change the water absorption curve and reduce the sum water absorption absolutely. However, they also cannot decrease the first 10 min water absorption rate. SiN material is the best one for reducing the water absorption compared to C and Si.

From Figure 4a, for the modified recycled coarse aggregate with (5–10) mm particle size, the water absorption is ordered as SiN-500 nm > SiN-20 nm > Si-150 nm > Si-300 nm > C. Comparing to the unmodified recycled coarse aggregate, by the end of 60 min, the sum water absorption can be decreased to 1.93%, 2.47%, 2.64%, 3.70% and 4.16%. The decreasing amplitude reached 66.1%, 56.6%, 53.7%, 35.0% and 27.0%, respectively. From Figure 4b, for the modified recycled coarse aggregate with (10–20) mm particle size, the water absorption is ordered as SiN-500 nm > SiN-20 nm > C > Si-300 nm > Si-150 nm. The 60 min sum water absorption can be decreased to 2.43%, 2.54%, 3.08%, 3.19% and 3.65%. The decreasing amplitude reached 50.5%, 48.3%, 37.3%, 35.0% and 25.8%, respectively. From the date above, it can be seen that the same modified material has different effects on the different recycled coarse aggregate. Using the same modified material, the water absorption reducing amplitude of the (5–10) mm particle size recycled coarse aggregate is more than the one with (10–20) mm particle size.

To analyze the reason for the different modified effects from C, Si, SiN materials, the particle size and the chemical properties may be the main two reasons. As we all know, there are a lot of pores in recycled coarse aggregate due to the existence of the sticking mortar. According to the previous study, the pore diameter of the mortar ranges from nanometer size to millimeter size [44]. However, the pore which can determine the water absorbing ability of the mortar is the capillary pore. The proportion of the capillary pore is about 0–40% in cement-based mortars, and its size is among (100–1000) nm [45]. In order to decrease the water absorption of the recycled coarse aggregate, the particle size which is used for blocking the capillary pore has to be smaller than 50 μm. So, the materials selected in the experiment are all suitable. Ordinarily, the smaller the particle is, the easier it can permeate into and block the pores in mortar. From Figure 4, this regularity is not remarkable. The water absorption of the recycled coarse aggregate modified with SiN-500 nm is less than the one modified with SiN-20 nm. Based on Figure 4b, this regularity also happens. The water absorption of the recycled coarse aggregate modified with Si-300 nm is less than the one modified with Si-150 nm. So, there may be other reasons leading to this result that need to be studied, such as detecting the modified aggregate pore distribution to see the amount of the rest capillary or observing the interspace of the capillary pore to see how much the interspace of the pore is occupied by the modified particle. Maybe these methods can explain the phenomenon that the smaller particle has weaker blocking ability.

The chemical properties of these particles can also have an effect on the water absorption of the recycled coarse aggregate. The wrapping materials can be separated into three kinds. One is pure sluggish material such as the silicon nitride. The second is half activity material such as the silica fume. The third one is activity material such as cement. The sluggishness material can not react with the water. It is only used as a filling material to fill the capillary pore of the mortar sticking on the recycled coarse aggregate. The half activity material can react with the water, not immediately, but sometime later. For example, the silica fume, if you add it to the cement base slurry, the silica fume can react with water slowly after the 28-d curing period. So, during the steeping process of recycled coarse aggregate in the slurry, the silica fume can absorb more water than the sluggish material. The water of the recycled coarse aggregate modified with silica fume slurry is composed of two parts, one part is from the pores which are not blocked by the silica fume slurry and the other part is from the reacting between the silica fume and the water. The active material can react with water almost immediately as long as it comes across the water. For example, the cement, the cement-based slurry will be wrapped on the recycled coarse aggregate and then dried. When testing the water absorption of the modified recycled coarse aggregate, the water that the aggregate absorbed can also be separated into two parts similar to the silica fume slurry. Because the water that the cement hydrate needs is much more than the silica fume hydrate, the water absorption of the recycled coarse aggregate modified by the cement slurry will be more than the ones modified by the silica fume slurry.

What is more, the dry cement slurry shell on the recycled coarse aggregate will continue to hydrate when it comes across the water. So, after 60 min, the cement will continue absorbing water to support the cement hydrate. The 24 h water absorption has been tested and displayed in Figure 5 to verify the final water absorption situation.

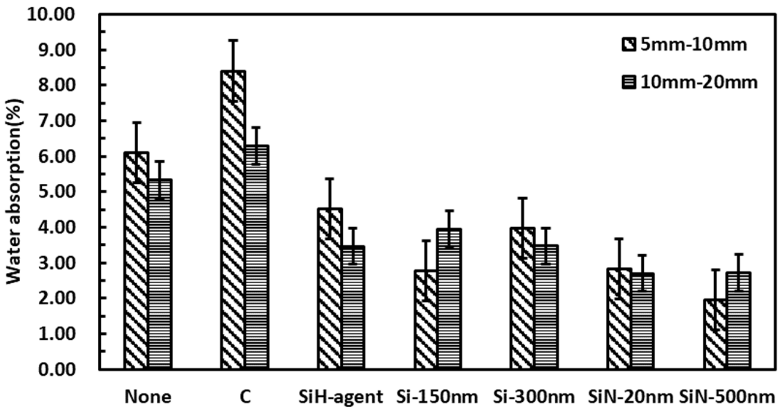


Figure 5. The 24 h water absorption of recycled coarse aggregate modified by different materials.

From Figure 5, it can be seen that almost every material can reduce the 24 h water absorption of the recycled coarse aggregate excluding the cement. Obviously, the water absorption of the aggregate modified by cement slurry is more than other materials and even more than the original recycled aggregate. This special phenomenon is due to the continuous cement hydrate reaction. For the (5–10) mm recycled coarse aggregate, the 24 h water absorption is ordered as C > None > SiH-agent > Si-300 nm > SiN-20 nm > Si-150 nm > SiN-500 nm. The water absorption is separately listed as 8.40%, 6.11%, 4.52%, 3.97%, 2.84%, 2.78%, 1.95%. The best modified material is SiN-500 nm, and it can reduce the water absorption of the recycled coarse aggregate by more than 60%. However, the price of the silicon nitride is much higher than the silica fume. The Si-150 nm is the second most excellent material. It can reduce the water absorption of the recycled coarse aggregate from 6.11% to 2.78%. The reduction in amplitude is about 54.5%. A little less than the SiN-500 nm. However, the price of the Si-150 nm is much less than the SiN-500 nm. If there is a large amount of the recycled coarse aggregate with (5–10) mm particle size, the Si-150 nm may be the best cost performance ratio material used for modifying these recycled coarse aggregate. For the (10–20) mm recycled coarse aggregate, the 24 h water absorption is ordered as C > None > Si-150 nm > Si-300 nm > SiH-agent > SiN-500 nm > SiN-20 nm. The water absorption is listed separately as 6.29%, 5.34%, 3.95%, 3.47%, 3.46%, 2.72%, 2.70%. For the (10–20) mm recycled coarse aggregate, the best modified material is SiN-20 nm and it can reduce the water absorption of the recycled coarse aggregate about 50%. Although the SiN material is better than other materials, the high price may limit its use for engineering.

From Sections 3.1 and 3.2, no matter the original recycled coarse aggregate or the modified ones, the water absorption of the recycled coarse aggregate is still higher than the natural coarse aggregate with water absorption under 2% according to the Chinese standard GB/T 14685-2011.

3.3. Concrete Performance Made by Modified Recycled Coarse Aggregate

Comparing the different effects on the concrete coming from the aggregates with different modified methods and different dry and wet conditions, the cement, silica fume with particle size 150 nm and the silicon nitride with 20 nm are selected. The dry modified recycled coarse aggregates are prepared by the method of Section 2.2.2. Number them as C-D, Si-150 nm-D and SiN-20 nm-D. The wet ones are also prepared following the Section 2.2.2 but without dry steps. Number them as C-W, Si-150 nm-W and SiN-20 nm-W.

Number the unmodified recycled coarse aggregate with None. The slump, compressive strength, splitting strength have been tested. The results are displayed in Figures 6–8. The mix proportion and the percentage of the recycled coarse aggregate are the same among these concretes. The details are shown in Table 9. The raw materials are all the same. The only difference is the kind of modified materials.

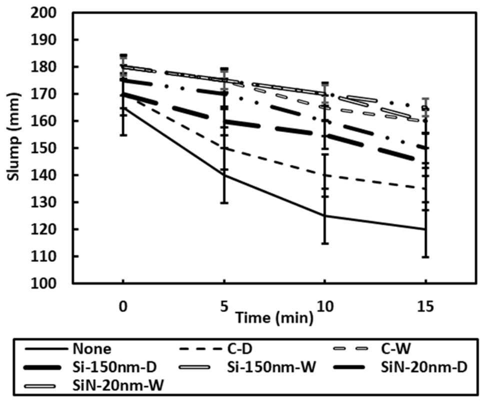


Figure 6. The slumps of concrete with different modified materials.

Figure 6 shows the slump change of the concretes with different modified materials and different dry or wet conditions among 0–15 min. First, from Figure 6, it can be seen that the slump will decrease with the time flow. However, the decreasing amplitude is different. The most important thing is that the wet modified recycled coarse aggregate is better than the dry ones. Not only is the initial slump of the concrete with the wet modified recycled coarse aggregate more than that of the concrete with the dry ones, but also the whole slump curve of the concrete with the wet modified recycled coarse aggregate is all on the top of the dry ones. From Figure 6, the initial slump can be ordered as SiN-20 nm-W (180 mm) = Si-150 nm-W = C-W > SiN-20 nm-D (175 mm) > Si-150 nm-D (170 mm) = C-D > None (165 mm). The 15th min slump can be ordered as SiN-20 nm-W (165 mm) > Si-150 nm-W (160 mm) = C-W > SiN-20 nm-D (150 mm) > Si-150 nm-D (145 mm) > C-D (135 mm) > None (120 mm). Using the initial slump minus the 15th min slump, the slump decreasing amplitude of the concrete with different modified materials between 0 min to 15 min is plot in Figure 7.

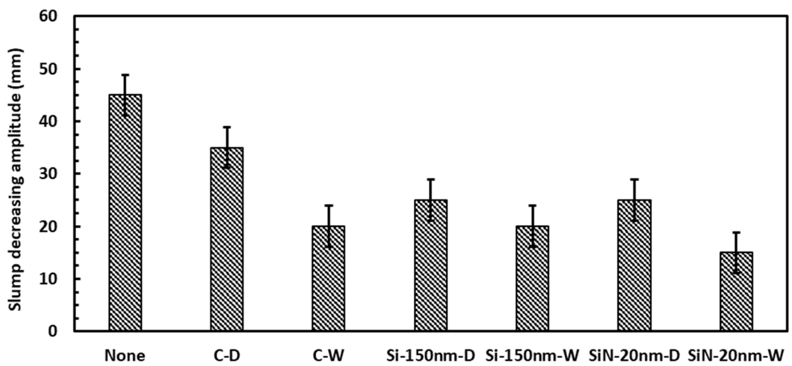


Figure 7. The slump decreasing amplitude of the concretes.

From Figure 7, the slump decreasing amplitude is ordered as SiN-20 nm-W (15 mm) > Si-150 nm-W (20 mm) = C-W > SiN-20 nm-D (25 mm) = Si-150 nm-D > C-D (35 mm) > None (45 mm). Actually, the less of the decreasing amplitude of the concrete is, the better of the concrete construction performance is. So, for keeping the slump of the concrete, the wet modified recycled coarse aggregate may be better than the dry ones. Considering the cost performance ratio, the cement is a more proper material than the silica fume and silicon nitride. So, during the real construction, using the cement slurry as the modified materials is a good selection.

The compressive strength and splitting strength of the concrete made by different modified materials are shown in Figure 8.

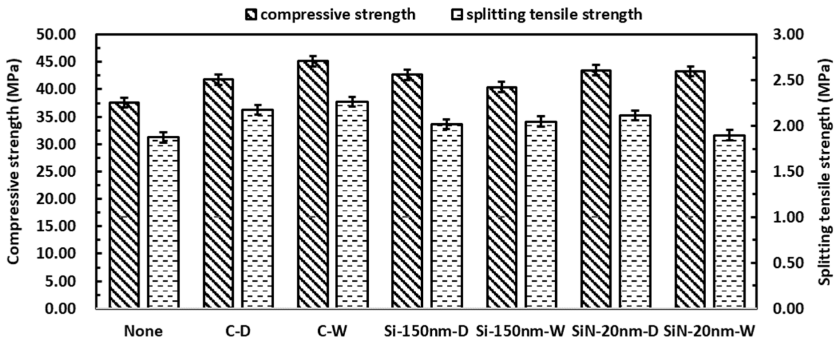


Figure 8. The mechanical property of the concrete made by different modified materials.

From Figure 8, the compressive strength of the concrete with different modified recycled coarse aggregate is plot on left axis and the splitting tensile strength is plot on the right one. Compared to the None group, the compressive strength and splitting tensile strength of all other groups are all increased. This phenomenon proves that the modified recycled coarse aggregate can enhance the mechanical property of the concrete.

From Figure 8, the compressive strength can be ordered as C-W > SiN-20 nm-D > SiN-20 nm-W > Si-150 nm-D > C-D > Si-150 nm-W. The increasing amplitude is listed separately as 20.12%, 15.60%, 15.16%, 13.48%, 11.08%, 7.45%. Unlike the slump rules, the concrete with wet modified recycled coarse aggregate is not better than the dry ones. The compressive strength of the concrete with SiN-20 nm-D modified the aggregate is more than the one with the SiN-20 nm-W modified the aggregate. The same situation also happens on the Silica fume and Cement. This phenomenon may be due to the aggregate with dry slurry shell wrapped can absorb more water than the aggregate with wet slurry on them. So, the water amount may decrease indirectly, and the water cement ratio is decreased at the same time. The smaller water cement ratio can lead to more compressive strength. The most important thing, from Figure 8, it also can be seen that the C-W group is the best one among these groups. From Figure 8, the splitting tensile strength can be ordered as C-W > C-D > SiN-20 nm-D > Si-150 nm-W > Si-150 nm-D > SiN-20 nm-W. The increasing amplitude is listed separately as 20.83%, 16.20%, 12.86%, 9.30%, 7.72%, 1.36%. So, the C-W is also the best group for the tensile strength. From the slump and mechanical performance analysis above, it can be seen that the C-W is definitely a good method for modifying the recycled coarse aggregate. Not only does it have good slump maintain performance, good mechanical performance, but also it is cheaper than the silica fume and silicon nitride.

3.4. The Effect of the Mixing Style of the Aggregate with Cement Slurry Wrapped

From the above study results, the C-W is a good way to modify the recycled coarse aggregate. However, considering the cost and convenience, setting a slurry pool on the construction site for pre-absorb slurry is not a high performance-cost-ratio thing. So, the study tries to find a new convenient way to wrap the recycled coarse aggregate with cement slurry.

Actually, the mechanism of modified recycled coarse aggregate has a lower water absorption rate, mainly due to the cement slurry blocking the pore of the mortar on the recycled aggregate. The slump of the concrete with recycled coarse aggregate decreased mainly due to the pores in the mortar on the aggregate. So, if there is enough cement slurry that the recycled coarse aggregate can absorb sufficiently, the recycled concrete slump decreasing can be resolved. Based on this method, this study decided to mix enough cement slurry into the concrete during the mixing process in order to supply enough cement slurry for the un-wrapped recycled coarse aggregate.

The slump, mechanical performance of the concrete has been tested. The results are displayed in Figures 9 and 10.

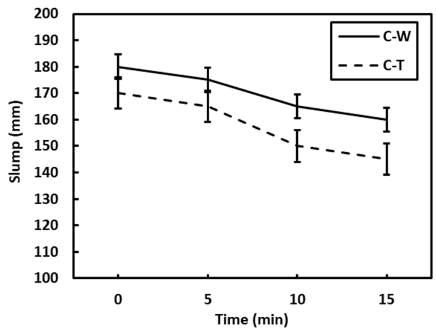


Figure 9. The slump of concrete (C-W group vs. C-T group).

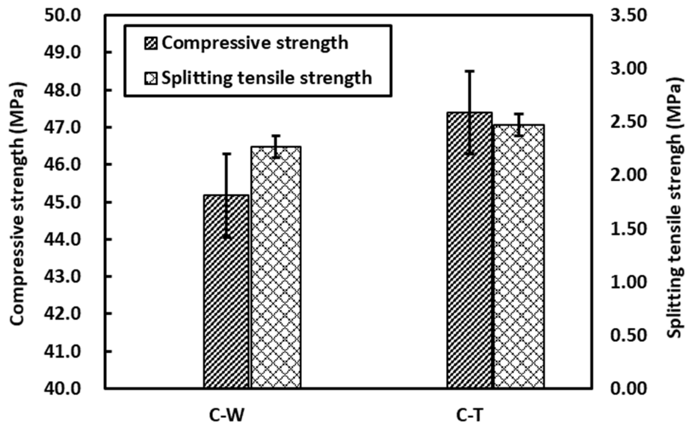


Figure 10. The mechanical performance of concrete (C-W group vs. C-T group).

From Figure 9, the slump of C-W group is more than the C-T group. For the initial slump of concrete, the C-W group which is 180 mm is also more than the C-T group which is 170 mm. For the slump decreasing amplitude, the C-W group which is 20 mm is less than the C-T group which is 25 mm. So, from the aspect of slump, the C-W is better than the C-T. This may be due to the C-W group aggregate being wrapped with cement slurry before being put into the blender. That means the pores of the mortar on the recycled coarse aggregate have been blocked in advance. So, the water absorption of the recycled coarse aggregate has been decreased before being put into the blender. During the mixing process in the blender, the wrapped recycled coarse aggregate has lower water absorption performance than the aggregate of the C-T group which has not been treated in advance. Meanwhile, the good thing is that the slump and the slump decreasing amplitude of concrete with C-T group aggregate are all still satisfied the requirement of the concrete construction.

From Figure 10, it can be seen that the compressive strength of C-W group which is 45.2 MPa is a little less than that of the C-T group which is 47.39 MPa. The splitting tensile strength shows the same rule as the compressive strength. So, the mechanical performance of concrete has different rules relating to the slump of concrete. The reason may be the extra cement slurry which is pre-mixing in the blender during the mixing process. The extra cement slurry takes more cement into the mixture. The more cement content the concrete has, the better compressive strength it will have.

From the slump and mechanical performance of the concrete, it can be seen that the C-T group can also satisfy the construction need as well as the C-W group. This result went quite well. That means there is no need to set up a slurry pool on a construction site. Good performance recycled concrete can be obtained by adding extra cement slurry directly.

4. Discussion

The test method of timely water absorption of the recycled coarse aggregate was invented first so that the whole curving of the water absorption of the recycled coarse aggregate can be plotted. Different recycled coarse aggregates have different water absorption curves. In the future, it may be a good way to distinguish them by the curves in concrete engineering.

Although the water absorption of the recycled coarse aggregate can be decreased by nano material slurry, some mechanisms still need to be studied. For example, how does the slurry flow in the tube of the pores? What is the diameter range of the particle which can block off the capillary pore maximum? Whether the status of the nano particle in the pores is stable enough to so that the cement concrete cannot be affected by the free nano materials.

The micro pore structure should be studied in the future paper. For example, comparing to recycled coarse aggregate without blocking how the distribution of the pore structure of the cement concrete changes. Maybe these studies can explain why the water absorption decreased by the nano material slurry.

Although the water absorption rate of the recycled coarse aggregate has been decreased by the cover shell of the slurry, more than 2% water absorption rate is still larger than natural aggregate with below 1% water absorption rate. So, to produce the cement concrete with recycled coarse aggregate, other methods such as using water reducer agent, optimizing the grading of the aggregate are all needed.

The durability of the cement concrete with recycled coarse aggregate needs to be studied especially the anti-frozen performance. This paper only studied the slump and compressive strength of the cement concrete with recycled coarse aggregate.

5. Conclusions

To obtain the water absorption curve of the recycled coarse aggregate from 0 min to 60 min, a new device has been invented. a new test method has been explored. Water absorption calculated for any time has been given. To reduce the water absorption of the recycled coarse aggregate, four kinds of materials are used such as cement, silica fume, nanometer silicon nitride and silicone hydrophobic agent. To find the effects of the recycled coarse aggregate on the concrete, the slump and mechanical performance of concretes have been tested. To find the mixing order effects, two kinds of mixing order have been studied. The results can be summarized as follows.

(1) A new device has been invented to record the water absorption continuously and calculate the water absorption rate automatically. The device consists of hardware and software. The hardware is shown in Figure 1. The software is designed to record and calculate the test data according to Equation (1). The test procedure has been given in Section 2.2.1. With this device, the water absorption curve can be plotted smoothly owing to the water absorption at any time can be recorded.

(2) During the first 10 min, the water absorption rate of the recycled coarse aggregates increases quickly. After 10 min, it becomes smoother. For different recycled coarse aggregate, about 90% amount of water has been absorbed in the former 10 min. The water absorption of the aggregate with (5–10) mm particle size is absolutely more than the one with (10–20) mm particle size.

(3) The 0 min–10 min water absorption of the modified recycled coarse aggregate is significantly reduced. C, Si, SiN can absolutely reduce the water absorption amount, and SiN is the best one. For the SiN-50 nm, it can reduce the first 10 min and the 60 min water absorption from above 4.5% to below 2.5%. It can also reduce the 24 h water absorption from above 5.3% to below 2.8%. For the amplitude of the 60 min water absorption, it is more obvious in the (5–10) mm particle size aggregate than in the (10–20) mm ones.

(4) The water absorption of the aggregate modified by cement slurry is more than other materials and even more than the original recycled aggregate. This special phenomenon is due to the continuous cement hydrate reaction. After 60 min, the dry cement shell on the aggregate will continue absorbing the water to support the cement hydrate performance.
(5) For the slump decreasing amplitude, the wet modified recycled coarse aggregate is generally better than the dry ones. The C-W group has the best strength among all of the groups. Comparing the None group, both the compressive strength and the splitting tensile strength of the C-W group concrete have been increased more than 20%.
(6) The slump of C-W group is better than the C-T group. The mechanical performance is opposite. The strength of the C-T group is larger than that of the C-W group. The reason may be the extra cement slurry which is pre-mixing in the blender leading to better strength. Good performance recycled concrete can be obtained by adding extra cement slurry to the blender directly.

6. Patents

A kind of test method and facility for testing the water absorption of the recycled coarse aggregate. (Chinese patent code: ZL 2021 1 0316969.X).

Author Contributions: L.Y.: Conceptualization, Data curation, Investigation, writing-original draft, Writing—review and editing. S.L.: Funding support. Z.Z.: Writing—review and editing. Z.L.: Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been supported by two grants. One is from A Special Fund Item of Scientific and Technological Innovation (Item number 2019-C534) which is from Research Institute of Highway Ministry of Transport, China. The second one is from Shandong Highway Incorporated Company to Research Institute of Highway Ministry of Transport, China. The Technology Plan Item (Item number 2018BZ3) set up by Transportation Department of Shandong Province, China.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The raw materials were supported by Shandong Highway Incorporated Company to Research Institute of Highway Ministry of Transport, China.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the word reported in this paper.

References

1. Quan, H.-Z. Application overview and technical standards of recycled concrete in other countries. *J. Qingdao Technol. Univ.* **2009**, *30*, 87–92.
2. Poon, C.S.; Kou, S.C.; Lam, L. Influence of recycled aggregate on slump and bleeding of fresh concrete. *Mater. Struct.* **2007**, *40*, 981–988. [CrossRef]
3. Jin, R.; Li, B.; Elamin, A.; Wang, S.; Tsioulou, O.; Wanatowski, D. Experimental Investigation of Properties of Concrete Containing Recycled Construction Wastes. *Int. J. Civ. Eng.* **2018**, *16*, 1621–1633. [CrossRef]
4. Leite, M.B.; do Filho, F.; Lima, P.R. Workability study of concrete made with recycled mortar aggregate. *Mater. Struct.* **2013**, *46*, 1765–1778. [CrossRef]
5. Revathi, P.; Selvi, R.S.; Velin, S.S. Investigations on Fresh and Hardened Properties of Recycled Aggregate Self Compacting Concrete. *J. Inst. Eng. India Ser. A* **2013**, *94*, 179–185. [CrossRef]
6. Ju, M.; Park, K.; Park, W.J. Mechanical behavior of recycled fine aggregate concrete with high slump property in normal-and high-strtength. *Int. J. Concr. Struct. Mater.* **2019**, *13*, 61. [CrossRef]
7. Yehia, S.; Helal, K.; Abusharkh, A.; Zaher, A.; Istaitiyeh, H. Strength and Durability Evaluation of Recycled Aggregate Concrete. *Int. J. Concr. Struct. Mater.* **2015**, *9*, 219–239. [CrossRef]
8. Mo, K.H.; Ling, T.-C.; Cheng, Q. Examining the Influence of Recycled Concrete Aggregate on the Hardened Properties of Self-compacting Concrete. *Waste Biomass-Valorization* **2021**, *12*, 1133–1141. [CrossRef]

9. Wang, Z.; Wang, L.; Cui, Z.; Zhou, M. Effect of recycled coarse aggregate on concrete com-pressive strength. *Trans. Tianjin Univ.* **2011**, *17*, 229–234. [CrossRef]
10. Sharma, R. Laboratory Study on Effect of Construction Wastes and Admixtures on Compressive Strength of Concrete. *Arab. J. Sci. Eng.* **2017**, *74*, 373–3962. [CrossRef]
11. Zheng, Y.; Zhang, Y.; Zhang, P. Methods for improving the durability of recycled aggregate concrete: A re-view. *J. Mater. Res. Technol.* **2021**, *15*, 6367–6386. [CrossRef]
12. Su, Y.; Gu, S.; Chang, X.-L.; Li, J.-X. Experiment study on recycled coarse aggregate modified with heating method. *China Concr. Cem. Prod.* **2015**, *10*, 6–10.
13. Xiao, J.Z.; Wu, L.; Fan, Y.H. Test on modification of recycled coarse aggregate by micro wave heating. *Concrete* **2012**, *7*, 55–57.
14. Chen, M.-Z.; Zhong, J.-J.; Wu, S.-P.; Zhu, J.-Q.; Wang, D.-M. Physical properties research of modified recycled coarse aggregate. *High Way* **2011**, *7*, 198–201.
15. Li, L.; Xuan, D.; Chu, S.H.; Poon, C.S. Modification of recycled aggregate by spraying colloidal nano silica and silica fume. *Mater. Struct.* **2021**, *54*, 223. [CrossRef]
16. He, D.-Z. Japanese Concrete strengthening treatment technology. *Spec. Struct.* **2000**, *17*, 39.
17. Zeng, W.; Zhao, Y.; Zheng, H.; Poon, C.S. Improvement in corrosion resistance of recycled aggregate concrete by nano silica suspension modification on recycled aggregates. *Cem. Concr. Compos.* **2020**, *106*, 103476. [CrossRef]
18. Zhu, Y.N.; Zhang, H.R.; Meng, T.; Zhao, Y.X. Performance of nano-SiO_2 modified recycled aggregate concrete applied in a real project. *Concrete* **2014**, *7*, 138–144.
19. Li, K.; Zhang, B.; Yang, D.; Xiao, L.; Xia, J.; Zhou, Y. Research on Influence of Silane Emulsion Impregnation on Properties of Concrete Made of African Natural High Water Absorption Aggregate. *Subgrade Eng.* **2016**, *5*, 114–118.
20. Li, Y. *Improvement of Recycled Concrete Aggregate Properties by CO_2 Curing*; Hunan University: Changsha, China, 2014; Volume 5.
21. Wang, J.H.; Geng, O.; Li, F.M. Experiment on effect of several measures by modifying recycled coarse ag-gregate on improving compressive strength of concrete. *J. Archit. Civ. Eng.* **2016**, *33*, 91–97.
22. Choi, H.; Choi, H.; Lim, M.; Inoue, M.; Kitagaki, R.; Noguchi, T. Evaluation of the mechanical perfaormance of low-quality recycled aggregate through interface enhancement between cement matrix and coarse aggregate by surface modification technology. *Int. J. Concr. Struct. Mater.* **2016**, *10*, 87–97. [CrossRef]
23. Shaban, W.M.; Yang, J.; Su, H.; Liu, Q.F.; Tsang, D.C.; Wang, L.; Xie, J.; Li, L. Properties of recycled concrete aggregates strengthened by different types of pozzolan slurry. *Constr. Build. Mater.* **2019**, *216*, 632–647. [CrossRef]
24. Wang, Y.; He, F.; Wang, J.; Hu, Q. Comparison of Effects of Sodium Bicarbonate and Sodium Carbonate on the Hydration and Properties of Portland Cement Paste. *Materials* **2019**, *12*, 1033. [CrossRef]
25. Wang, Y.; He, F.; Wang, J.; Wang, C.; Xiong, Z. Effects of calcium bicarbonate on the properties of ordinary Portland cement paste. *Constr. Build. Mater.* **2019**, *225*, 591–600. [CrossRef]
26. Wang, H.; Sun, X.; Wang, J.; Monteiro, P.J. Permeability of Concrete with Recycled Concrete Aggregate and Poz-zolanic Materials under Stress. *Materials* **2016**, *9*, 252. [CrossRef] [PubMed]
27. Xie, J.; Huang, L.; Guo, Y.; Li, Z.; Fang, C.; Li, L.; Wang, J. Experimental study on the compressive and flexural behaviour of recycled aggregate concrete modified with silica fume and fibres. *Constr. Build. Mater.* **2018**, *178*, 612–623. [CrossRef]
28. Shaban, W.M.; Yang, J.; Su, H.; Mo, K.H.; Li, L.; Xie, J. Quality Improvement Techniques for Recycled Concrete Aggregate: A review. *J. Adv. Concr. Technol.* **2019**, *17*, 151–167. [CrossRef]
29. Tam, V.W.; Gao, X.; Tam, C.M.; Chan, C. New approach in measuring water absorption of recycled aggregates. *Constr. Build. Mater.* **2008**, *22*, 364–369. [CrossRef]
30. Rajagopal, A. *Automated Laboratory Testing Methods for Specific Gravity and Absorption Verified to Match the Current Method Results Final Report*; Fine Aggregates; Infrastructure Management and Engineering Inc.: Cincinnati, OH, USA, 2009; p. 82.
31. Xing, J.; Yu, L. Selection of concrete pores filling materials and its applicability analysis. *New Build. Mater.* **2019**, *6*, 51–55.
32. Bhasya, V.; Bharatkumar, B.H. Mechanical and durability properties of concrete produced with treated recycled concrete aggregate. *ACI Mater. J.* **2018**, *115*, 209–217. [CrossRef]
33. *ASTM C127*; Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption. ACM: New York, NY, USA, 2014.
34. *GB/T 14685-2011*; PRC National Standard. Pebble and Crushed Stone for Construction. SAC: San Bernardino, CA, USA, 2011.
35. *JGJ/T 322-2013*; PRC Building Industrial Standard. Technical Specification for Test of Chloride Ion Content in Concrete. China Building Industry Press: Beijing, China, 2013.
36. *ASTM C188*; Standard Test method for Density of Hydraulic Cement. ASTM: West Conshohocken, PA, USA, 2009.
37. *ASTM C204*; American Association State Highway and Transportation Officials Standard. ASTM: West Conshohocken, PA, USA, 2016.
38. Alibaba Website. Available online: https://detail.1688.com/offer/38086091044.html?spm=a2615.7691456.autotrace-offerGeneral.19.cdb64761jjVk5z (accessed on 16 February 2022).
39. Alibaba Website. Available online: https://detail.1688.com/offer/586664215978.html?spm=a312h.2018_new_sem.dh_002.7.fd22203fBgQA2H&cosite=baidujj_pz&tracelog=p4p&clickid=c56accd8033e4c69a22de5c1dc865c13&sessionid=1677a50ffad3af2e79ebedc3d04940e3 (accessed on 16 February 2022).
40. *GB/T 175*; PRC National Standard. Common Portland Cement. China Standards Press: Beijing, China, 2020.

41. *GB/T 14684*; PRC National Standard. Sand for Construction. China Standards Press: Beijing, China, 2011.
42. *ASTM C143/C143-M*; Slump of Hydraulic Cement Concrete. ASTM: West Conshohocken, PA, USA, 2012.
43. *ISO 4012:1978-11*; Concrete—Determination of Compressive Strength of Test Specimens. ISO: Geneva, Switzerland, 1978.
44. Xu, Q. The Research on Spatial and Frequency Distribution of the Pore Structure of Cement Based Materials. Master's Thesis, Southeast University of China, Nanjing, China, 2014.
45. Zhao, H.; Ding, J.; Huang, Y.; Tang, Y.; Xu, W.; Huang, D. Experimental analysis on the relationship between pore structure and capillary water absorption characteristics of cement-based materials. *Struct. Concr.* **2019**, *20*, 1750–1762. [CrossRef]