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Article

Experimental Research on the Physical and Mechanical Properties of Concrete with Recycled Plastic Aggregates

Haikuan Wu[1,2], Changwu Liu[1,2,*], Song Shi[1,2] and Kangliang Chen[1,2]

[1]State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, 610065, China
[2]College of Water Resource and Hydropower, Sichuan University, Chengdu, 610065, China
*Corresponding Author: Changwu Liu. Email: liuchangwu@scu.edu.cn
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Abstract: In order to study the effect of recycled plastic particles on the physical and mechanical properties of concrete, recycled plastic concrete with 0, 3%, 5% and 7% content (by weight) was designed. The compressive strength, splitting tensile strength and the change of mass caused by water absorption during curing were measured. The results show that the strength of concrete is increased by adding recycled plastic into concrete. Among them, the compressive strength and the splitting tensile strength of concrete is the best when the plastic content is 5%. With the increase of plastic content, the development speed of early strength slows down. Silane coupling agent plays a positive role in the strength of recycled plastic concrete. The water absorption saturation of concrete has been basically completed in the early stage. The addition of silane coupling agent makes the porosity of concrete reduce and the water absorption of concrete become poor. By summing up the physical and mechanical properties of recycled plastic concrete, it could be found that the addition of recycled plastic was effective for the modification of concrete materials. Under the control of the amount of recycled plastic, the strength of concrete with recycled plastic aggregates can meet the engineering requirements.

Keywords: Compressive strength; recycled plastic concrete; splitting tensile strength; water absorption; mechanical properties

1 Introduction

In recent years, people pay more and more attention to plastic pollution. At the same time, people's understanding of environmental hazards is gradually deepened. Polytetrafluoroethylene plastics are widely used in the industries of atomic energy, national defense, aerospace, electronics, electrical, chemical, machinery, instrument, architecture, textile, metal surface treatment, pharmacy, medical treatment, textile, food, metallurgy and smelting, etc., as high and low temperature resistant, corrosion-resistant materials, insulation materials, anti-sticking coating, etc., making it an irreplaceable product [1–3]. As polytetrafluoroethylene (PTFE) was widely used in these industries, it would inevitably lead to the increase of waste PTFE. The waste of PTFE would be produced in the process of synthesis, processing, secondary processing and application of PTFE. PTFE has excellent performance [1,3], high price and great recycling value, and its recycling has been highly valued. Scholars all over the world have carried out active research on this problem, and put forward various suggestions and methods for the treatment and utilization of waste plastics [4–6]. As a civil engineer, it is a very good choice to apply waste plastics to ordinary concrete after a certain degree of treatment. It can not only solve environmental pollution and achieve sustainable development, but also improve the performance of concrete.

In the past, many scholars introduced recycled aggregate into concrete to study its basic properties [7–15]. Some scholars introduced fiber into concrete to increase the tensile strength and other properties of concrete [16–18]. Some scholars introduced some lightweight aggregate into concrete to study the performance of lightweight concrete [19–22]. At the same time, some experts introduced solid waste plastic particles into concrete [23–26]. Marzouk et al. [27] introduced waste plastic bottles into concrete, studied the volume density and mechanical properties of the material, and studied the relationship between the mechanical properties and microstructure of the material by means of SEM. The compressive strength and flexural strength of the composite were not affected by the replacement of sand with volume fraction less than 50% by PET with particle size upper limit of 5 mm. Panyakapo et al. [28] introduced the application of thermosetting plastics as admixtures in the mix proportion of lightweight concrete. The plastic not only led to a low dry density concrete, but also a low strength. Foti [29] simply cut waste plastic bottles into fibers and introduced them into concrete to study the possibility of improving the ductility of concrete. Saikia et al. [30] studied the influence of the size and shape of recycled polyethylene terephthalate (PET) aggregate on the mixing and hardening properties of concrete. With the addition of PET aggregate, the compressive strength, splitting tensile strength, elastic modulus and flexural strength of concrete decreased, and with the increase of the content of PET aggregate, the decrease of these properties increased. de Oliveira et al. [31] studied the basic mechanical properties of this fiber-reinforced mortar by adding PET bottle fiber cut by simple machine into the mortar. The addition of PET fiber could improve the flexural strength and toughness of mortar. Iucolano et al. [32] Studied the effect of recycled plastic aggregate on the physical and mechanical properties of mortar. The replacement of recycled plastics increased the porosity, reduced the bending and compression strength, and increased the water vapor permeability. Arulrajah et al. [33] evaluated three kinds of recycled waste plastic particles with linear low-density polyethylene filled with calcium carbonate, high-density polyethylene (HDPE) and low-density polyethylene (LDPE) as raw materials, and with crushed brick (CB) and recycled asphalt pavement (RAP) as mixtures. The strength, rigidity and elastic modulus of the blends were evaluated. Coppola et al. [34] used a new polymer aggregate with special properties to replace natural sand to prepare light mortar. This mortar has many advantages, such as reducing consumption of natural sand, reducing structural self-weight and improving aggregate and cement slurry. When increasing the amount of sand replacement, it was observed that the consistency of mortar decreased, as expected, the mechanical properties also decreased. Thorneycroft et al. [35] found that it was feasible to replace 10% sand with recycled plastic, which could save 820 million tons of sand every year. Through proper mix design, the structural performance of waste plastic concrete could be maintained.

Through previous studies, it could be found that the research on other recycled aggregate concrete has been very mature, the polytetrafluoroethylene (PTFE) type of plastic was not used in production of concrete frequently in the previous studies. Due to the different selection of materials, there were some differences in the conclusions of each scholar. In this work, waste polytetrafluoroethylene recycled plastic was introduced into concrete. Through mechanical tests, the compressive and splitting tensile properties of recycled polytetrafluoroethylene plastic concrete were studied. The water absorption property of this kind of concrete was studied by the weight change test in water. Finally, it was found that the properties of recycled plastic concrete were improved to some extent. Therefore, it is of great potential to introduce recycled polytetrafluoroethylene plastic into concrete.

2 Materials and Methods

2.1 Materials

In this test, P.C 32.5R composite Portland cement was used as cement, with specific parameters as shown in Tab. 1. Fine aggregate was river sand, with specific parameters as shown in Tab. 2. Coarse aggregate was crushed stone, with specific parameters as shown in Tab. 3. Sieves curves of the fine and coarse aggregate were shown in Fig. 1. Plastic particles were polytetrafluoroethylene (see Fig. 2), with particle diameter of 1–2 mm, with specific parameters as shown in Tab. 4. Silane coupling agent was KH560, with specific parameters as shown in Tab. 5.

Table 1: Cement parameters

Factory standard	Strength grade	Compressive strength (MPa)	Initial setting time (h)	Final setting time (h)	Cement fineness (%)	Hydration heat	Sulfate resistance	MgO (%)	SO_3 (%)	Stability
P.C 32.5R	32.5R	40.4	3	3.88	3	Qualified	moderate heat	high	2.85	2.57

Table 2: Fine aggregate parameters

Apparent density (g/cm^3)	Bulk density (g/cm^3)	Void fraction (%)	Fineness modulus	Water absorption rate (%)
2.540	1.469	42.17	2.47	1.3

Table 3: Coarse aggregate parameters

Apparent density (g/cm^3)	Bulk density (g/cm^3)	Void fraction (%)	Particle size range (mm)	Water absorption rate (%)
2.550	1.574	38.27	5–10	0.4

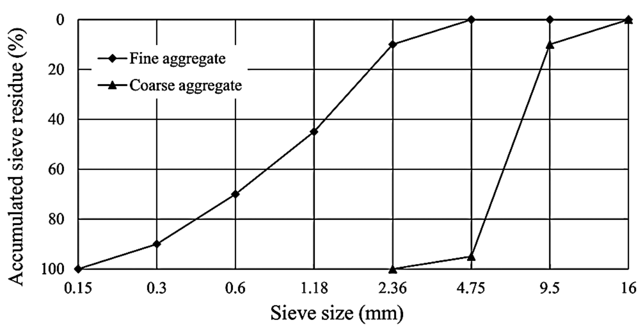

Figure 1: Sieves curves of the fine and coarse aggregate

2.2 Methods

The mix proportion of recycled plastic concrete was water: cement = 0.40, sand ratio was 0.3, plastic particles were added into the concrete, and the admixture did not replace any component of the concrete. The amount of admixture took sand as a reference, accounting for 0, 3%, 5% and 7% of the mass proportion of cement, and the amount of silane coupling agent was 0.5% of the mass proportion of plastic particles. The concrete mix was shown in Tab. 6. HJW-30 concrete horizontal mixer was used for

Figure 2: Polytetrafluoroethylene plastic particles

Table 4: Polytetrafluoroethylene plastic parameters

Density (g/cm3)	Friction coefficient	Heat resistance (°C)	Corrosion resistance	Tensile strength (MPa)	Bending strength (MPa)	Modulus of elasticity in bending (MPa)	Compressive strength (MPa)	Modulus of elasticity in compression (MPa)	Elongation (%)	Tensile modulus of elasticity (MPa)	Water absorption rate	Poisson's ratio
2.1–2.3	≤0.1	240~260	strong	≥30	20.7	700	12.9	280	250~350	≥3.92	<0.01	0.4

concrete mixing. Firstly, stone and cement were added into the mixer for 120 s, then sand was added into the mixer for 120 s, and then plastic particles and water were added into the mixer for 120 s. Finally, the mixed concrete was put into a group of plastic molds with three samples of 100 × 100 × 100. the sample was placed on the vibration table and vibrated until the surface slurry flows out, then the surface of the sample was ground flat, and finally the sample was separated from the mold after standing in the air for 24 hours. The specimens were cured in tap water at 20 ± 2°C, and the compressive strength, splitting tensile strength and mass of concrete were measured at 7 and 28 days of curing age. The strength testing machine was a 200 t uniaxial pressure testing machine. The load control rate was 4000 N/s for compressive strength test and 400 N/s for splitting tensile strength test. Electronic platform scale instrument was used for mass test.

In the process of strength test, the surface of the specimen and the upper and lower pressure plates of the instrument should be wiped clean first. Then the specimen needed to be placed on the lower pressing plate or base plate of the testing machine. The bearing surface of the test piece should be perpendicular to the top surface at the time of forming. The center of the specimen should be aligned with the center of the lower pressing plate of the testing machine. Then the test machine was started. When the upper pressing plate was close to the specimen or steel base plate, adjust the ball socket to make the contact even. The load should be applied continuously and evenly during the test. When the specimen was close to failure and starts to deform rapidly, the accelerator of the testing machine should be stopped until failure. The final failure load was recorded. In the process of mass test, the mass of the sample was measured at the beginning of curing, the 7th day of curing and the 28th day of curing respectively.

3 Results and Discussion

3.1 Compressive Strength

The recycled plastic concrete specimens were divided into four groups according to the quantity of admixture. The compressive strength test results are shown in Tab. 7.

Table 5: Parameters of silane coupling agent KH560

Appearance	Density (g/cm^3)	Molecular weight	Flash point (°C)	Boiling point (°C)	Solubility	Refractive index (ND25)
Transparent liquid	1.068~1.075	236	110	290	Soluble in water with pH = 3.4~4	1.4275~1.4300

Table 6: Material consumption per cubic meter of concrete (unit: kg)

Cement	Water	Fine aggregate	Coarse aggregate	Recycled plastic	Silane coupling agent
466.7	186.68	520.58	1214.68	0	0
466.7	186.68	520.58	1214.68	14	0.07
466.7	186.68	520.58	1214.68	23.34	0.12
466.7	186.68	520.58	1214.68	32.69	0.16

Table 7: Compressive strength of concrete (MPa)

Plastic content (%)	7 d (coupling agent)	28 d (coupling agent)	28 d (normal)
0	36.57	38.13	38.13
3	42.4	43.76	39.90
5	42.96	47.00	40.78
7	34.18	45.39	43.38

Fig. 3 shows the compressive strength of recycled plastic concrete at 7 and 28 days. When the proportion of plastic particles was 0, 3% and 5%, the compressive strength of concrete was rising, while when the proportion of plastic particles was 7%, the compressive strength of concrete dropped sharply, and the compressive strength of concrete with 5% plastic particles reached the peak. In addition, the compressive strength of the concrete with 3% and 5% admixtures for 7 and 28 days was higher than that of the ordinary concrete. However, the compressive strength of 7 days curing concrete with 7% plastic particles was less than that of ordinary concrete, while the compressive strength of 28 day curing concrete was greater than that of ordinary concrete. At the same time, it could be seen that the compressive strength of ordinary concrete in 7 days curing period is 95% of that in 28 days, that in 7 days curing period with 3% recycled plastic concrete was 96% of that in 28 days, that in 7 days curing period with 5% recycled plastic concrete was 91% of that in 28 days, and that in 7 days curing period with 7% recycled plastic concrete was 75% of that in 28 days. It could be seen that with the increase of plastic content, the development speed of early strength slowed down. In the previous studies, the compressive strength would decrease with the increase of plastic content [28,32,26]. But in this work, because plastic did not replace the material in concrete, it was only the pure use of plastic waste, so it was equivalent to adding more materials to concrete, which eventually led to the increase of strength compared with ordinary concrete.

Fig. 4 shows the compressive strength of recycled plastic concrete with or without silane coupling agent. From the overall trend, the compressive strength of recycled plastic concrete with silane coupling agent was generally higher than that of concrete without silane coupling agent. When the content of recycled plastic was 3%, the compressive strength of concrete with silane coupling agent was 1.09 times of that without silane

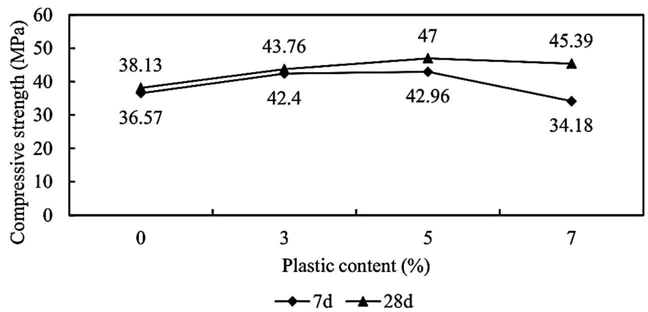

Figure 3: Comparison of compressive strength of recycled plastic concrete at 7 and 28 days

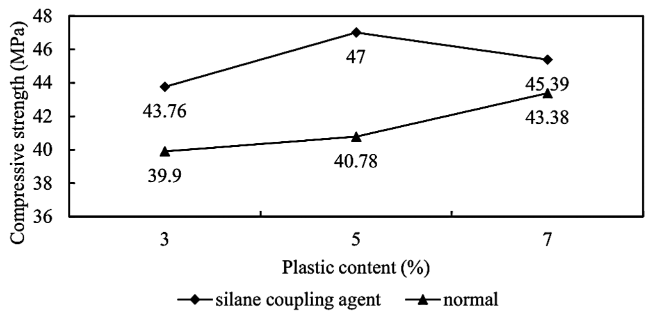

Figure 4: Comparison of compressive strength of recycled plastic concrete with or without silane coupling agent

coupling agent. When the content of recycled plastic was 5%, the compressive strength of concrete with silane coupling agent was 1.15 times of that without silane coupling agent. When the content of recycled plastic was 7%, the compressive strength of concrete with silane coupling agent was 1.05 times of that without silane coupling agent. The compressive strength of concrete mixed with silane coupling agent reached the maximum value when the amount of plastic was 5%, and the compressive strength curve of concrete without silane coupling agent showed a gradual increasing trend. It can be seen that silane coupling agent plays a positive role in the compressive strength of recycled plastic concrete. According to previous studies [36,37], silane coupling agent could improve the interfacial adhesion between materials, so adding silane coupling agent could improve the compressive strength of concrete.

3.2 Splitting Tensile Strength

The splitting tensile strength test results are shown in Tab. 8.

Fig. 5 shows the comparison of splitting tensile strength of recycled plastic concrete with curing age of 7 days and 28 days. It could be seen from the overall trend of the strength curve that the splitting tensile strength of recycled plastic concrete at 28 days was generally higher than that of ordinary concrete, while the splitting tensile strength of concrete at 7 days was lower than that of ordinary concrete when the plastic content was 5% and 7%. It could be seen that with the increase of plastic content, the development of early splitting tensile strength of concrete was not perfect. The splitting tensile strength of concrete with 7 days curing age reached the maximum value when the recycled plastic content was 3%, and the splitting tensile strength of concrete with 5% and 7% recycled plastic content gradually decreased. The splitting tensile strength of concrete with recycled plastic content of 5% reached the maximum value in the curing period of 28 days, and the splitting tensile strength of concrete with recycled plastic content of 7% began to decrease. When the content of recycled plastic was 0, 3%, 5%

Table 8: Splitting tensile strength of concrete (MPa)

Plastic content (%)	7 d (coupling agent)	28 d (coupling agent)	28 d (normal)
0	3.735	3.826	3.826
3	4.098	5.078	3.136
5	3.542	5.370	3.759
7	3.494	4.492	3.706

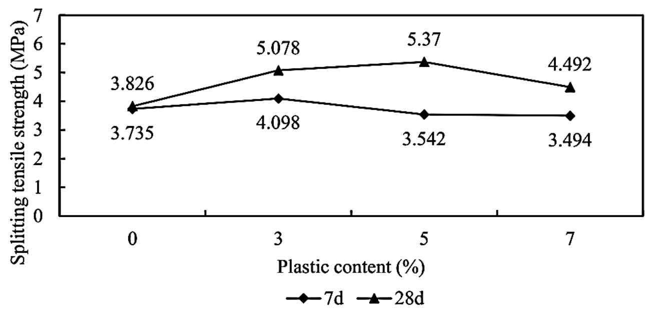

Figure 5: Comparison of splitting tensile strength of recycled plastic concrete with curing age of 7 days and 28 days

and 7%, the cleavage tensile strength of concrete can reach 97%, 80%, 66% and 77% of the 28 days strength when the curing age is 7 days. It could be seen that the early cleavage tensile strength of concrete mixed with plastic was generally reduced. In previous studies, most people found that with the increase of plastic content, the splitting tensile strength decreased [38,39]. However, in this study, the splitting tensile strength of concrete is stronger than that of ordinary concrete. There are two main reasons: on the one hand, silane coupling agent increases the cohesion of plastic and concrete materials [36]; on the other hand, the tensile property of plastic itself is more excellent [1].

Fig. 6 shows the contrast of splitting tensile strength of recycled plastic concrete with or without silane coupling agent. From the overall trend of the strength curve, it could be seen that the splitting tensile strength of concrete with silane coupling agent was generally higher than that without silane coupling agent, and the splitting tensile strength of concrete reached the peak value when the plastic content was 5%. When the content of recycled plastic was 3%, the splitting tensile strength of concrete with silane coupling agent was 1.61 times of that of concrete without silane coupling agent. When the content of recycled plastic

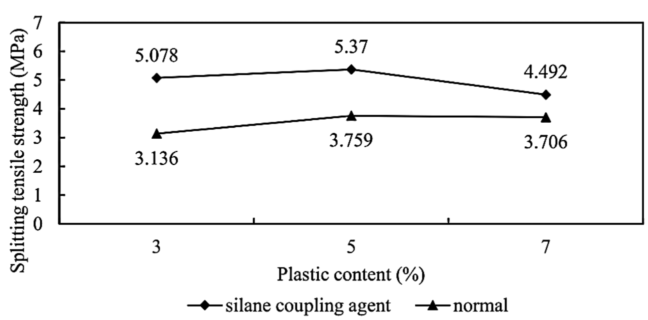

Figure 6: Comparison of splitting tensile strength of recycled plastic concrete with or without silane coupling agent

was 5%, the splitting tensile strength of concrete with silane coupling agent was 1.42 times of that of concrete without silane coupling agent. When the content of recycled plastic was 7%, the splitting tensile strength of concrete with silane coupling agent was 1.21 times of that of concrete without silane coupling agent. It could be seen that silane coupling agent played a positive role in the splitting tensile strength of recycled plastic concrete. As the silane coupling agent can improve the compressive strength of concrete, it is the same principle that silane coupling agent can improve the splitting tensile strength of concrete.

The relationship between compressive strength and splitting tensile strength of recycled plastic concrete was analyzed. It could be seen that the compressive strength of recycled plastic concrete with silane coupling agent was 9.79 times, 10.34 times, 12.12 times and 9.78 times of splitting tensile strength respectively when the curing age was 7 days, the plastic content was 0, 3%, 5% and 7%. The compressive strength of recycled plastic concrete with silane coupling agent at 28 days was 9.96 times, 8.62 times, 8.75 times and 10.10 times of splitting tensile strength respectively. When the content of plastics was 3%, 5% and 7%. The compressive strength of recycled plastic concrete without silane coupling agent was 12.72 times, 10.85 times and 11.71 times of splitting tensile strength at the curing age of 28 days. In the previous studies, the compressive strength of concrete was about 10 times of the splitting tensile strength [40,41]. In this study, it was found that the law of recycled plastic concrete was basically consistent with previous studies.

3.3 Mass Change

The mass change results are shown in Tab. 9.

Fig. 7 shows the mass change of recycled plastic concrete in 7 and 28 days. According to the overall trend of the histogram, when the content of plastic particles was 3%, the water absorption quality of the concrete will change the most when it leaves the mold, that was to say, the water absorption was the most. With the increase of the content of plastic particles, the change of water absorption gradually decreases, and when the content of plastic particles was 7%, the water absorption was less than that of ordinary concrete. According to the comparison of 7 days and 28 days water absorption of concrete, the water absorption of 7 days concrete was generally less than 28 days, in which the water absorption of 7 days concrete with 0,3%, 5% and 7% plastic particles was 8 g, 6 g, 7 g and 9 g lower than that of 28 days respectively. It could be seen that the water absorption saturation of concrete was basically completed in the early stage, with little change in the later stage.

Table 9: Concrete mass change (g)

Plastic content (%)	7 d (coupling agent)	28 d (coupling agent)	28 d (normal)
0	32	40	40
3	37	43	37
5	33	40	38
7	28	37	43

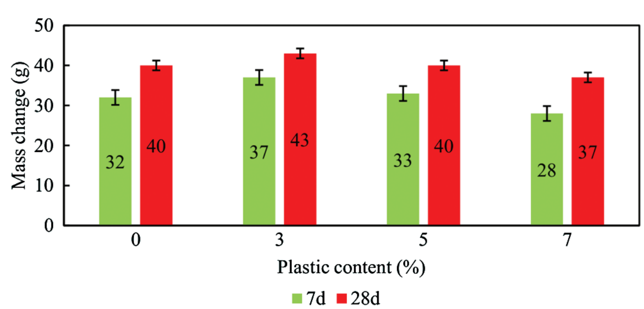

Figure 7: Comparison of 7 days and 28 days mass change of recycled plastic concrete

Fig. 8 shows the mass change of recycled plastic concrete with or without silane coupling agent. From the overall trend, the water absorption of concrete with silane coupling agent decreased with the increase of plastic content, while that of concrete without silane coupling agent increased with the increase of plastic content. It could be seen that with the increase of silane coupling agent, the porosity of recycled plastic concrete decreased and the water absorption became poor. According to previous studies [36,37], silane coupling agent could improve the interfacial adhesion between materials. With the increase of silane coupling agent, the compactness of concrete becomes better and the mass changes less.

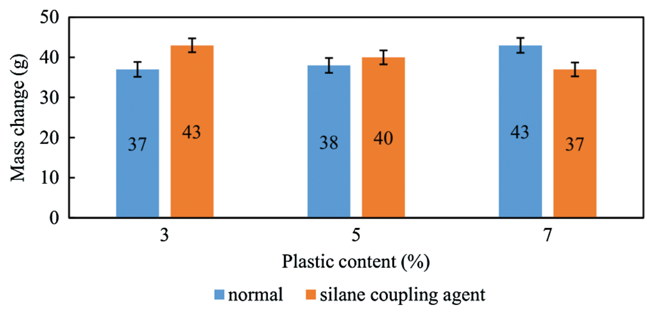

Figure 8: Comparison of mass change of recycled plastic concrete with or without silane coupling agent

4 Conclusions

Through the analysis and discussion of the test data of recycled plastic concrete, the following conclusions can be drawn:

1. The addition of recycled plastics to concrete increases the strength of concrete, and the compressive strength reaches the best when the recycled plastics content is 5% in the 7-day and 28-day curing age of concrete; the splitting tensile strength reaches the best when the recycled plastics content is 3% in the 7-day curing age of concrete, and reaches the best when the recycled plastics content is 5% in the 28-day curing age of concrete.
2. When the recycled plastic content is 0, 3%, 5% and 7%, the 7-day compressive strength of concrete can reach 95%, 96%, 91% and 75% of the 28 days strength respectively, and the 7-day splitting tensile strength of concrete can reach 97%, 80%, 66% and 77% of the 28-day strength. It can be seen that with the increase of plastic content, the hydration heat of concrete slows down, and the development speed of early strength slows down.
3. When the content of recycled plastic is 3%, 5% and 7%, the compressive strength of concrete with silane coupling agent is 1.09 times, 1.15 times and 1.05 times of that without silane coupling agent, and the splitting tensile strength of concrete with silane coupling agent is 1.61 times, 1.42 times and 1.21 times of that without silane coupling agent, respectively. It can be seen that silane coupling agent plays a positive role in the strength of recycled plastic concrete.
4. When adding silane coupling agent, the compressive strength of concrete is 9.79 times, 10.34 times, 12.12 times and 9.78 times of splitting tensile strength when the curing age is 7 days, the amount of plastic is 0, 3%, 5% and 7%, respectively. When the curing age is 28 days, the compressive strength of concrete is 9.96 times, 8.62 times, 8.75 times and 10.10 times of splitting tensile strength respectively when the plastic content is 0, 3%, 5% and 7%. When no silane coupling agent is added, the compressive strength of concrete is 12.72 times, 10.85 times and 11.71 times of splitting tensile strength when the curing age is 28 days, the plastic content is 3%, 5% and 7%, respectively.
5. The water absorption of concrete in 7 days is generally less than 28 days. The water absorption of concrete in 7 days with 0, 3%, 5% and 7% plastic particles are 8 g, 6 g, 7 g and 9 g lower than that in 28 days

respectively. It can be seen that the water absorption saturation of concrete is basically completed in the early stage, with little change in the later stage. With the increase of silane coupling agent, the porosity of concrete decreases and the water absorption becomes poor.

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References

1. Dhanumalayan, E., Joshi, G. M. (2018). Performance properties and applications of polytetrafluoroethylene (PTFE)—a review. *Advanced Composites and Hybrid Materials, 1(2),* 247–268. DOI 10.1007/s42114-018-0023-8.
2. Tanabe, T., Sugie, S. (1977). Application of expanded polytetrafluoroethylene for construction of cardiovascular shunts. *Artificial Organs, 1(1),* 144.
3. Hironaka, S. (2004). Characteristics and applications of PTFE composites. *Journal of Japanese Society of Tribologists, 49(7),* 573–577.
4. Fuks, S. L., Khitrin, S. V., Vologzhanina, Y. V., Pinaeva, L. N., Mikhalitsyna, Y. S. et al. (2015). Cloused cycle of production of ulltrafine polytetrafluoroethylene and new areas of use of fluoropolymer manufacture waste. *Russian Journal of Applied Chemistry, 88(11),* 1800–1807. DOI 10.1134/S10704272150110105.
5. Xiang, D. H., Tao, K. M. (2007). The mechanical and tribological properties of PTFE filled with PTFE waste powders. *Journal of Applied Polymer Science, 103(2),* 1035–1041. DOI 10.1002/app.25296.
6. Wang, L. B., Cheng, Q. L., Qin, H. F., Li, Z. C., Lou, Z. S. et al. (2017). Synthesis of silicon carbide nanocrystals from waste polytetrafluoroethylene. *Dalton Transactions, 46(9),* 2756–2759. DOI 10.1039/C6DT04865J.
7. Chen, J., Su, Y. W., Lei, T., Gu, S. (2011). Study on strength estimating of recycled concrete based on rebound method and ultrasonic-rebound combined method. *Advanced Materials Research, 243–249,* 5470–5474.
8. James, M. N., Choi, W., Abu-Lebdeh, T. (2011). Use of recycled aggregate and fly ash in concrete pavement. *American Journal of Engineering and Applied Sciences, 4(2),* 201–208. DOI 10.3844/ajeassp.2011.201.208.
9. Hruringza, J., Topic, J., Hlubocky, L., Plachy, T. (2016). Development of mechanical properties of cement based composites with recycled concrete aggregate. *Applied Mechanics and Materials, 825,* 11–14. DOI 10.4028/www.scientific.net/AMM.825.11.
10. Amorim Junior, N. S., Silva, G. A. O., Dias, C. M. R., Ribeiro, D. V. (2019). Concrete containing recycled aggregates: estimated lifetime using chloride migration test. *Construction and Building Materials, 222,* 108–118. DOI 10.1016/j.conbuildmat.2019.06.136.
11. Abdulmatin, A., Tangchirapat, W., Jaturapitakkul, C. (2019). Environmentally friendly interlocking concrete paving block containing new cementing material and recycled concrete aggregate. *European Journal of Environmental and Civil Engineering, 23(12),* 1467–1484. DOI 10.1080/19648189.2017.1355265.
12. Braga, A. M., Silvestre, J. D., de Brito, J. (2017). Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates. *Journal of Cleaner Production, 162,* 529–543. DOI 10.1016/j.jclepro.2017.06.057.
13. Li, B., Ling, T. C., Yu, J. G., Wu, J., Chen, W. (2019). Cement pastes modified with recycled glass and supplementary cementitious materials: properties at the ambient and high temperatures. *Journal of Cleaner Production, 241*. DOI 10.1016/j.jclepro.2019.118155.

14. Kubissa, W., Jaskulski, R., Reiterman, P. (2017). Ecological concrete based on blast-furnace cement with incorporated coarse recycled concrete aggregate and fly ash addition. *Journal of Renewable Materials, 5(1),* 53–61. DOI 10.7569/JRM.2017.634103.
15. Wang, L., Lenormand, H., Zmamou, H., Leblanc, N. (2019). Effect of soluble components from plant aggregates on the setting of the lime-based binder. *Journal of Renewable Materials, 7(9),* 903–913. DOI 10.32604/jrm.2019.06788.
16. Ghomi, S., El-Salakawy, E. F. (2019). Seismic behavior of GFRP-reinforced concrete interior beam-column-slab subassemblies. *Journal of Composites for Construction, 23(6)*. DOI 10.1061/(ASCE)CC.1943-5614.0000980.
17. Mohit, S. A., El-Salakawy, E. (2019). Rehabilitation of reinforced concrete circular columns with sprayed-glass fiber-reinforced polymer composites. *Journal of Composites for Construction, 23(6)*. DOI 10.1061/(ASCE)CC.1943-5614.0000973.
18. Sahani, A. K., Samanta, A. K., Singharoy, D. K. (2019). Mechanical behaviour of fire-exposed fibre-reinforced sustainable concrete. *Journal of Structural Fire Engineering, 10(4),* 482–503.
19. Liu, X., Wu, T., Liu, Y. (2019). Stress-strain relationship for plain and fibre-reinforced lightweight aggregate concrete. *Construction and Building Materials, 225,* 256–272. DOI 10.1016/j.conbuildmat.2019.07.135.
20. Mohseni, E., Tang, W., Wang, S. (2019). Development of thermal energy storage lightweight structural cementitious composites by means of macro-encapsulated PCM. *Construction and Building Materials, 225,* 182–195. DOI 10.1016/j.conbuildmat.2019.07.136.
21. Kurpinska, M., Grzyl, B., Kristowski, A. (2019). Cost analysis of prefabricated elements of the ordinary and lightweight concrete walls in residential construction. *Materials (Basel, Switzerland), 12(21),* 3629. DOI 10.3390/ma12213629.
22. Solak, A. M., Tenza-Abril, A. J., Baeza-Brotons, F., Benavente, D. (2019). Proposing a new method based on image analysis to estimate the segregation index of lightweight aggregate concretes. *Materials (Basel, Switzerland), 12(21),* 3642. DOI 10.3390/ma12213642.
23. Faraj, R. H., Sherwani, A. F. H., Daraei, A. (2019). Mechanical, fracture and durability properties of self-compacting high strength concrete containing recycled polypropylene plastic particles. *Journal of Building Engineering, 25,* 12. DOI 10.1016/j.jobe.2019.100808.
24. Saikia, N., de Brito, J. (2012). Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. *Construction and Building Materials, 34,* 385–401. DOI 10.1016/j.conbuildmat.2012.02.066.
25. Faraj, R. H., Ali, H. F. H., Sherwani, A. F. H., Hassan, B. R., Karim, H. (2020). Use of recycled plastic in self-compacting concrete: a comprehensive review on fresh and mechanical properties. *Journal of Building Engineering, 30,* 101283. DOI 10.1016/j.jobe.2020.101283.
26. Gu, L., Ozbakkaloglu, T. (2016). Use of recycled plastics in concrete: a critical review. *Waste Management, 51,* 19–42. DOI 10.1016/j.wasman.2016.03.005.
27. Marzouk, O. Y., Dheilly, R. M., Queneudec, M. (2007). Valorization of post-consumer waste plastic in cementitious concrete composites. *Waste Management, 27(2),* 310–318. DOI 10.1016/j.wasman.2006.03.012.
28. Panyakapo, P., Panyakapo, M. (2008). Reuse of thermosetting plastic waste for lightweight concrete. *Waste Management, 28(9),* 1581–1588. DOI 10.1016/j.wasman.2007.08.006.
29. Foti, D. (2011). Preliminary analysis of concrete reinforced with waste bottles PET fibers. *Construction and Building Materials, 25(4),* 1906–1915. DOI 10.1016/j.conbuildmat.2010.11.066.
30. Saikia, N., de Brito, J., (2014). Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Construction and Building Materials, 52,* 236–244. DOI 10.1016/j.conbuildmat.2013.11.049.
31. de Oliveira, L. A. P., Castro-Gomes, J. P. (2011). Physical and mechanical behaviour of recycled PET fibre reinforced mortar. *Construction and Building Materials, 25(4),* 1712–1717. DOI 10.1016/j.conbuildmat.2010.11.044.
32. Iucolano, F., Liguori, B., Caputo, D., Colangelo, F., Cioffi, R. (2013). Recycled plastic aggregate in mortars composition: effect on physical and mechanical properties. *Materials & Design (1980–2015), 52,* 916–922. DOI 10.1016/j.matdes.2013.06.025.

33. Arulrajah, A., Yaghoubi, E., Wong, Y. C., Horpibulsuk, S. (2017). Recycled plastic granules and demolition wastes as construction materials: resilient moduli and strength characteristics. *Construction and Building Materials, 147,* 639–647. DOI 10.1016/j.conbuildmat.2017.04.178.
34. Coppola, B., Courard, L., Michel, F., Incarnato, L., Di Maio, L. (2016). Investigation on the use of foamed plastic waste as natural aggregates replacement in lightweight mortar. *Composites Part B: Engineering, 99,* 75–83. DOI 10.1016/j.compositesb.2016.05.058.
35. Thorneycroft, J., Orr, J., Savoikar, P., Ball, R. J. (2018). Performance of structural concrete with recycled plastic waste as a partial replacement for sand. *Construction and Building Materials, 161,* 63–69. DOI 10.1016/j.conbuildmat.2017.11.127.
36. Li, W., Huang, Z., Wang, X. C., Wang, J. W. (2014). Proportion of tensile strength and compressive strength of the crumb rubber concrete modified by silane coupling agent. *Advanced Materials Research, 953–954,* 1520–1523. DOI 10.4028/www.scientific.net/AMR.953-954.1520.
37. Wang, G. M., Kong, Y., Shui, Z. H. (2015). Influence of surface treated metakaolin with coupling agent on the properties of concrete. *Materials and Structures, 48(1–2),* 261–267. DOI 10.1617/s11527-014-0471-8.
38. Colangelo, F., Cioffi, R., Liguori, B., Iucolano, F. (2016). Recycled polyolefins waste as aggregates for lightweight concrete. *Composites Part B: Engineering, 106,* 234–241. DOI 10.1016/j.compositesb.2016.09.041.
39. Mohammadinia, A., Wong, Y. C., Arulrajah, A., Horpibulsuk, S. (2019). Strength evaluation of utilizing recycled plastic waste and recycled crushed glass in concrete footpaths. *Construction and Building Materials, 197,* 489–496. DOI 10.1016/j.conbuildmat.2018.11.192.
40. Xiao, J. Z., Li, J. B., Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research, 35(6),* 1187–1194. DOI 10.1016/j.cemconres.2004.09.020.
41. Ding, Y., Dai, J. G., Shi, C. J. (2016). Mechanical properties of alkali-activated concrete: a state-of-the-art review. *Construction and Building Materials, 127,* 68–79. DOI 10.1016/j.conbuildmat.2016.09.121.