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A study of the durability properties of waste tire rubber applied to self-compacting concrete

Wang Her Yung [a,*], Lin Chin Yung [a], Lee Hsien Hua [b]

[a] Department of Civil Engineering and Disaster Mitigation Technology, National Kaohsiung University of Applied Sciences, Kaohsiung 807, Taiwan, ROC

[b] Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, ROC

HIGHLIGHTS

- ▶ We provide the feasibility of concrete containing waste tire rubber powder in situ.
- ▶ The optimal amount of rubber replacement is suggested for concerning of strength.
- ▶ The addition of 5% waste tire rubber powder could increase in anti-sulfate corrosion.
- ▶ By comparing to the ordinary concrete, SCRC had high electrical resistance properties.
- ▶ Using waste tire rubber powder can enhance the durability of SCRC.

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ABSTRACT

This study used waste tire rubber as a recycled material and replaced part of the fine aggregate by waste tire rubber powder filtered through #30 and #50 sieves to produce self-compacting rubber concrete (SCRC). Part of the fine aggregate was replaced with waste tire rubber powder that had been passed through sieves at volume ratios of 5%, 10%, 15% and 20%, respectively, to produce cylinder specimens and obtain the optimal replacement value. Replacing part of the normal sand with waste tire rubber powder of different degrees of fineness at different ratios is discussed.

The results showed that when 5% waste tire rubber powder that had been passed through a #50 sieve was added, the 91 day compressive strength was higher than the control group by 10%. Additionally, the shrinkage was higher with an increase in the amount of waste rubber, and reached its maximum at 20%. The ultrasonic pulse velocity decreased when more powder was added, and the 56 day electrical resistance exceeded 20 kΩ-cm and was increased with the addition of more powder. Meanwhile, both the ultrasonic pulse velocity and the electrical resistance were in a favorable linear relationship with the compressive strength. The addition of 5% waste tire rubber powder brought about a significant increase in anti-sulfate corrosion. Using waste tire rubber powder can enhance the durability of self-compacting rubber concrete.

1. Introduction

Energy saving and carbon reduction have become a global movement. The optimal application of resources, efficient construction, quality improvements and economical construction costs have become urgent issues as Taiwan promotes overall economic development, strives to improve living standards and solves the problems of shortages in sandstone resources and the labor market.

Along with the development of ready-mixed concrete industry throughout the world, other industries have also shown progress related to this industry. One of the most important of them is the admixture sector. Concrete has gained improved properties with chemical and mineral admixtures [1,2]. Self-compacting concrete (SCC) is a special type of concrete material where vibration/compaction is avoided by adding super plasticizers into the fresh mixtures to achieve a similar level of compaction. This relatively new technology is gaining increased popularity in the construction industry as it provides an environmentally friendly and safer way of producing concrete without compromising its quality [3–8]. With limited sandstone resources, adding recycled materials to SCC has positive effects, such as replacing the sand with reservoir silt and waste liquid crystal glass [9–11]. In recent decades, worldwide growth of

* Corresponding author. Tel.: +886 7 3814526x5237; fax: +886 7 3961321.
E-mail addresses: wangho@kuas.edu.tw (W.H. Yung), hhlee@mail.nsysu.edu.tw (L.H. Hua).

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automobile industry and increasing use of car as the main means of transport have tremendously boosted tyre production. This has generated massive stockpiles of used tyres. In the early 1990s, extensive research projects were carried out on how to use used tyres in different applications [12]. Over 1,00,000 tons of waste tires are annually generated in Taiwan, and this number is increasing, but there is no solution for disposing of waste tires at present. The US ranks first in the world with 270 million waste tires generated annually, followed by Japan with over 110 million waste tires generated each year [13]. Because of the environmental threat associated with waste tires, their proper disposal has attracted significant attention in recent years. In the United States alone, 290 million tires are generated per year, along with an existing 275 million tires currently stockpiled throughout the nation [14].

Waste tires need a larger storage space than other waste due to their large volume and fixed shape. They are unlikely to be decomposed, as burying the waste tires would shorten the service life of the burial ground and have low economic benefit. In addition, long-term buried waste tires often emerge from the burial ground surface or destroy the anti-leakage cover of the burial ground [15], and the exposed waste tires accumulate water that may breed bacteria, molds, insects or mice. In the case of fire, waste tires generate toxic gases, such as dioxin, that could result in severe pollution problems [16]. Therefore, effectively recovering and reusing waste tires is an urgent and important issue [17]. Landfill disposal, which is the most common method, will be drastically reduced in the near future due to the recent introduction of European Union directives that include significant restrictions on this practice in favor of alternatives oriented toward material and energy recovery. Furthermore, the disposal of used tires in landfills, stockpiles or illegal dumping grounds increases the risk of accidental fires with uncontrolled emissions of potentially harmful compounds. In order to properly dispose of these millions of tires, the use of innovative techniques to recycle them is important. Rubber tire can be used in a variety of civil and non-civil engineering applications such as in road construction, in geotechnical works, as a fuel in cement kilns and incineration for production of electricity or as an aggregate in cement-based products [18]. And rubber wastes can be used as fuel for cement kilns, as feedstock for making carbon black and as reefs in marine environments [19–21]. Concerning the reuse of recycled rubber in mortars and concrete, extensive studies have been conducted on used tyre modified concrete and mortars. Results have indicated that rubberized concrete mixtures show lower density, increased toughness and ductility, higher impact resistance, lower compressive and splitting tensile strength, and more efficient sound insulation [22,23]. However, some authors have suggested that the loss in strength might be minimized by prior surface treatment of the rubber particles [24]. The introduction of rubber particles significantly increases the strain capacity of materials. However, rubber in cement paste enhances the toughness of the composite. Although the mechanical strengths are reduced, composites containing 50% rubber particles satisfy the basic requirement of lightweight construction materials and correspond to “class II” according to the RILEM classification system [16]. Several studies have indicated that the presence of crumb rubber in concrete lowers the mechanical properties (compressive and flexural strength) compared to those of conventional concrete. The lower strength is due to the lack of bonding between the rubber crumb and Portland cement. This decrease in strength was found to be directly proportional to the rubber content. The sizes of the rubber crumbs also appear to have influence on the strength. The coarse grading of rubber crumbs lowers the compressive strength in comparison with finer grades [25].

Self-compacting concrete is considered as a concrete that can be placed and compacted under its own weight without any vibration, assuring the complete filling of formworks, even when access is hindered by narrow gaps between reinforcement bars. In order to achieve such behavior, the fresh concrete must show both high fluidity and good cohesiveness [26]. The high fluidity of the concrete is obtained by adding a super plasticizer [27]. Apart from reliability and constructability, advantages such as the elimination of noise in processing plants and a reduction in construction time and labor costs have been cited as benefits of self-compacting concrete [28]. On site, delivery delays are frequent and ambient temperatures have been found to influence the workability of the concrete [29]. The stability of SCC can be enhanced by incorporating fine materials such as limestone powder, fly ash and ground granulated blast furnace slag. The addition of these materials increases the cement content, leading to a significant increase in material costs and other negative effects on the concrete properties [30]. However, in spite of the fine filler presence (usually with an average size of about 10–30 μm), when promoting the formation of a very compact microstructure and reaching high values of compressive strength, the failure behavior of SCC is still brittle [31]. Due to the difference in mixture design and placement and consolidation techniques, the durability of SCC may be different than that of normal concrete, and thus needs thorough investigation [32].

In order to solve the above problem, this study replaced part of the sand with waste tire rubber powder, which was then mixed into SCRC. We tested the fresh properties and hardening properties of SCRC based on different ratios of added waste tire rubber to find out the optimal replacement level. The proposed method can provide a sandstone source and solve the problem of sandstone shortages, as well as recycle waste materials.

2. Experimental plan

2.1. Material

Type I cement of a Taiwan brand was used that conformed to ASTM C150 specifications. F type fly ash was used that conformed to ASTM C618 specifications. The slag used was produced by the China Hi-Ment Corp. and conformed to CNS 12549 specifications. Table 1 shows the physical and chemical characteristics of the cement, fly ash and slag. The aggregate used was from the Li-gang River and conformed to ASTM C33 specifications for concrete material. The waste tire rubber powder was produced by the Taiwan Water–jet Company. As shown in Fig. 1, Waste tire rubber powder passing No. #30 sieves (0.6 mm) and No. #50 sieves (0.3 mm). The water used conformed to ASTM C94 for water for concrete mixing. Carboxylic acid was used as a high flow agent and conformed to SCRC requirements.

2.2. Test variable

In this study, #30, #50 and #30 + #50 sieved waste tire rubber powder was added to the SCC. #30 + #50 sieved waste tire rubber powder half and half. The fixed water-binder ratio was 0.35, and the fixed binding agent was 600 kg/m^3.

Table 1
Chemical components and physical properties of cement, fly ash and slag.

Test item	Cement	Fly ash	Slag
Chemical analysis (%)			
SiO_2 (S)	21.41	48.27	33.35
Al_2O_3 (A)	5.53	38.23	14.76
Fe_2O_3 (F)	2.66	4.58	0.59
S + A + F	30.0	91.08	48.7
CaO	64.16	2.84	40.64
MgO	1.33	2.92	7.12
SO_3	2.60	0.75	0.50
TiO_2	–	1.42	–
Na_2O	–	0.21	–
K_2O	–	1.16	–
LOI	–	5.38	0.16
Physical properties			
Fineness (m^2/kg)	349	435	405
Specific gravity	3.14	2.00	2.89
#325 Residues (%)	5.9	–	2.0

Note: Cement C_3S, C_2S, C_3A and C_4AF: 60.8%, 12.29%, 7.74%, 10.1%; $C_3S + C_3A$: 20.03%.

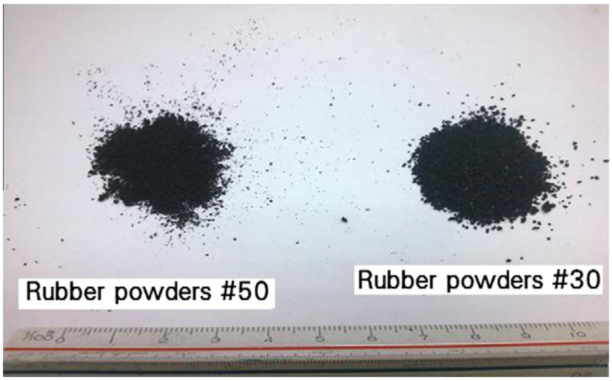

Fig. 1. Waste tire rubber powder passing No. #30 and No. #50 sieves.

The sand was replaced with 0%, 5%, 10%, 15% and 20% waste tire rubber powder (Table 2 shows the mix proportions) to make the cylinder specimens. The fresh property tests were carried out first, and the hardening property tests and durability property tests were carried out at different times. Mixing the waste tire rubber powder of different degrees of fineness would result in preferable results according to Sukontasukkul [32]. Thus, the third mix proportion of this study used mixed waste tire rubber powder from #30 and #50 sieves as the variable.

2.3. Experimental method

The dimensions of the specimens for the compressive strength, ultrasonic, electric resistivity and sulfate attack tests were 100 × 200 mm. In addition, 285 mm × 750 mm × 750 mm cylinders were used in the shrinkage tests.

In this study, compressive strength tests were conducted according to ASTM C39 and ASTM C192 at 7, 28 and 91 days, respectively, and the ultrasonic tests were performed according to ASTM C597 at 7, 28, and 91 days. Shrinkage of the mortar after drying was assessed according to ASTM C827 at 1, 7, 28 and 91 days. The surface resistivity tests were performed according to ASTM C876 and employed four-point resistance meters made by Swiss Proceed to measure the resistivity upon contact with different concrete sections at 7, 28 and 91 days. The anti-corrosion properties of concrete that had been cured for three days were examined according to ASTM C1012 in terms of weight loss after eight cycles of alternate drying and soaking in sulfate solution.

3. Results and analysis

3.1. Properties of waste tire rubber powder

A waste tire is composed of rubber, carbon black, steel wire and nylon fiber. The main components include rubber, vulcanizing agent, vulcanization accelerator, accelerator, antioxidant, reinforcing agent, filler, softener and stain. Among these, rubber accounts for about 70.53% of the whole tire, and this rubber is composed of natural and synthetic organic compounds of petroleum. Currently, synthetic rubber is generally used. This synthetic rubber is composed of styrene–butadiene rubber (SBR) and butadiene rubber [33]. Carbon black is filled in the tire for reinforcing the vulcanized rubber; it is the filler for reinforcing the stabilization of the combination. Thermo-gravimetric analysis (TGA) of the waste tire rubber powder is shown in Fig. 2. The sieving analysis and physical properties are shown in Table 3.

3.2. Compressive strength

Table 4 and Fig. 3 shows that the compressive strength of three degrees of fineness and mix proportions reached a maximum on the 28th day. However, when 5% of the #50 sieved waste tire rubbers were added, the compressive strength was 96% of the control group. The compressive strength of other addition levels was low

Table 2
Mixture proportions of SCRC. Unit: kg/m^3.

No.		Binding materials			Coarse aggregate	Fine aggregate		Water	Admixture
		Cement	Slag	Fly ash		Sand	Rubber		
SCRC	0%					885	0		
SCRC30	5%					840.75	16.29		
SCRC50	10%	300	150	150	888	796.5	32.58	210	7.8
SCRC3050	15%					752.25	48.87		
	20%					708	65.16		

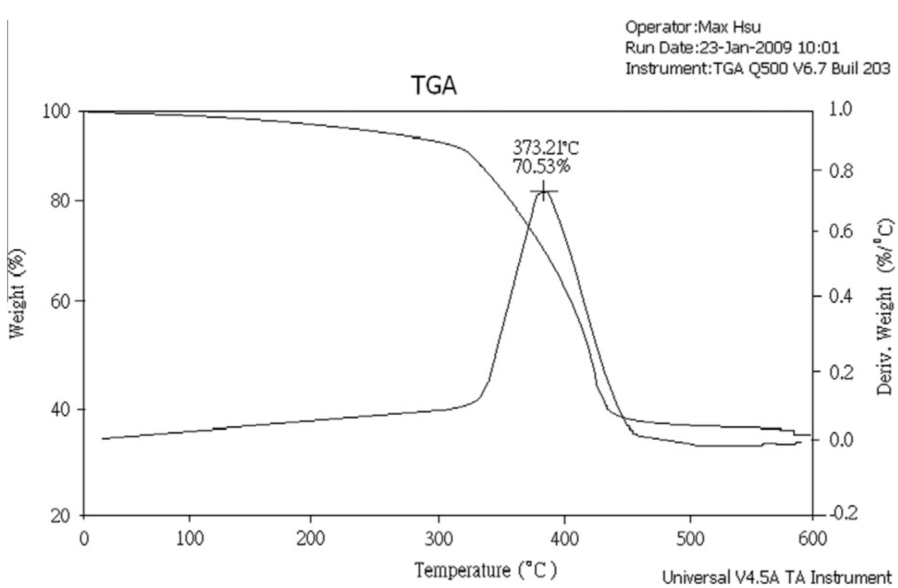

Fig. 2. TGA of the waste tire rubber powder.

Table 3
Sieve analysis and physical properties of waste rubber powder.

Sieve No.	#30	#50	#100	Pan	Fineness modulus	Specific gravity
#20–40	121	56.9	65.5	9.6	2.17	0.95
#50–100	2.1	165.5	135	1.8	1.56	0.95

Table 4
Compressive strength for SCRC. Unit: MPa (%).

Age	**1**	**7**	**28**	**56**	**91**
SCRC 0%	3.57(11)	22.9(71)	32.07(100)	32.3(101)	32.77(102)
SCRC30 (%)					
5	3.27(11)	22.39(77)	28.97(100)	30.92(107)	31.3(108)
10	2.54(10)	17.3(70)	24.89(100)	27(109)	27.6(111)
15	4.2(16)	20.6(77)	26.9(100)	29.08(108)	30.78(114)
20	3.38(15)	18(79)	22.8(100)	26.98(118)	27.64(121)
SCRC50 (%)					
5	39(10)	23.5(76)	30.94(100)	32.93(106)	35.73(115)
10	2.79(12)	17.95(76)	23.53(100)	26.54(113)	27.86(118)
15	3.23(14)	16.26(70)	23.4(100)	25.2(108)	27.19(116)
20	4.16(19)	17.85(82)	21.9(100)	24.73(113)	24.96(114)
SCRC3050 (%)					
5	1.96(8)	19.26(74)	25.9(100)	30.21(117)	30.68(118)
10	2.65(11)	18.66(78)	23.96(100)	26.54(111)	27.12(113)
15	0.95(5)	13.63(71)	19.21(100)	23.56(123)	25.35(132)
20	1.42(7)	14.29(74)	19.24(100)	21.36(111)	24.31(126)

Note: Strength of the age/strength of the 28 days age × 100%.

than that of the control group (32.07 MPa), and the compressive strength declined when the addition level was increased. This result proved that the compressive strength declined as the rubber addition increased, as stated by Hsiung [34], although the fineness of the waste tire rubber in this study was smaller. The addition level was only 5% of the total granular material. The strength of the concrete with waste tire rubber powder is generated after hydrate formation. When these hydrates are formed, the compressive strength of the concrete is increased. The compressive strength was higher than the control group by 10% after 91 days.

3.3. Ultrasonic pulse velocity

Generally speaking, the pulse velocity of coarse aggregate was larger than that of fine aggregate, which in turn was larger than of cement mortar. Therefore, the more coarse aggregate was present, with the same unit volume, the faster the pulse velocity was. In concrete, too much water and too many gaps can reduce the pulse velocity [35]. As shown in Fig. 4, the 7 day ultrasonic pulse velocities were 3614–3841 m/s, 3539–3834 m/s and 3605–3855 m/s, respectively, all of which were lower than the 3975 m/s value of the control group. The 28 day ultrasonic pulse velocity of the control group was 4180 m/s, whereas that of waste tire rubber powder that had been passed through #30 sieve was within the range of 4018–3810 m/s (4–9% lower). The 28 day ultrasonic pulse velocity of waste tire rubber powder that had been passed through a #30 sieve was within the range of 4003–3725 m/s (4–11% lower), whereas that of waste tire rubber powder that had been passed through #30 + #50 sieves was within the range of 4041–3810 m/s (3–9% lower). Fig. 5 shows that the linear regression relation, R^2, of the SCRC ultrasonic pulse velocities and compressive strengths was above 0.92, which was higher than the control group at $R^2 = 0.882$.

3.4. Shrinkage

As shown in Fig. 6, the change in length of 28 day SCRC of the control group was −0.0183%, and the average changes in the length of concrete with waste tire rubber powder that had been passed through #30, #50 and #30 + #50 sieves were −0.0294%, −0.0298% and −0.0308%, respectively, when 5% waste tire rubber powder was added. At this addition level, the change was the smallest, and the average change in the length of the three was −0.0248%, which was 35% higher than the control group. When 20% waste tire rubber powder was added, the change was the largest, and the average change in the length of the three was −0.0357%, which was 95% higher than the control group. Because part of the fine aggregate was rubber powder whose modulus of elasticity was much smaller than the other aggregate [19], its

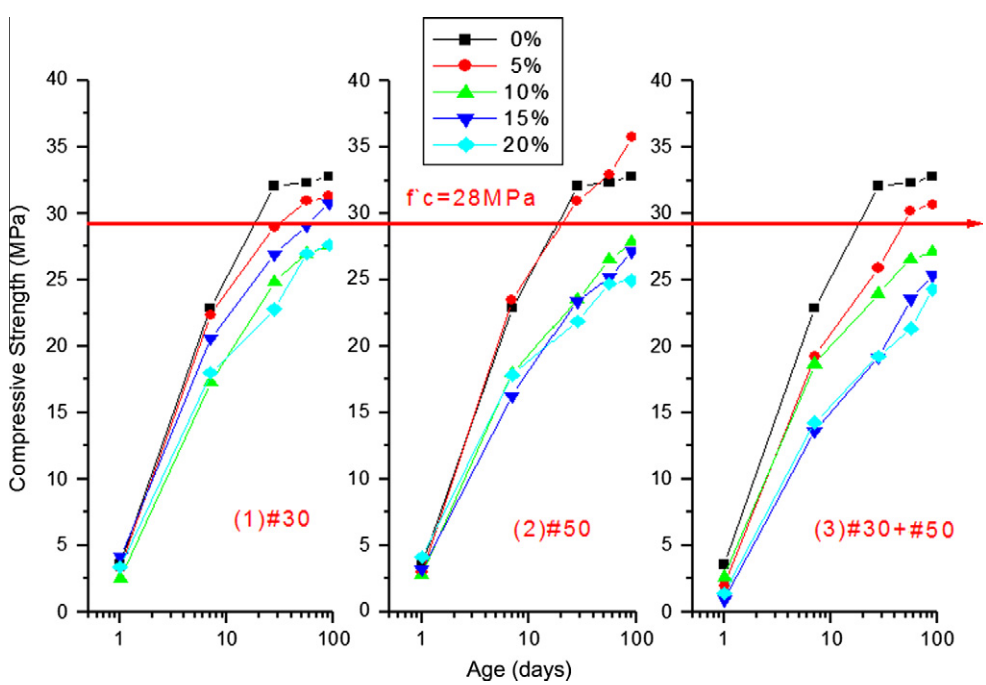

Fig. 3. Compressive strength for SCRC.

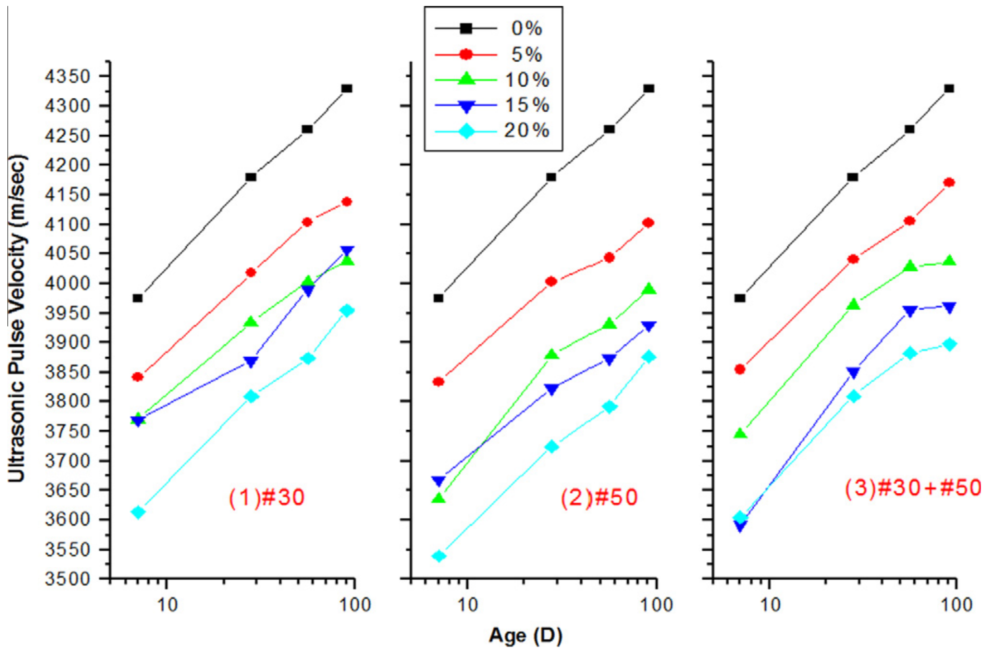

Fig. 4. Ultrasonic pulse velocity for SCRC.

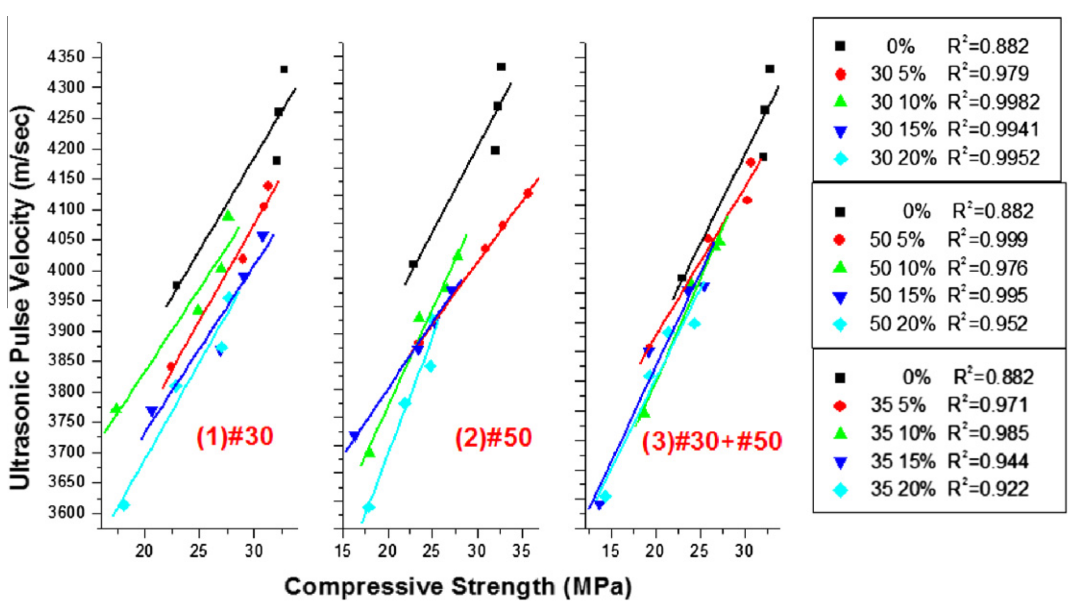

Fig. 5. Relationship between compressive strength and ultrasonic pulse velocity at different sieved.

capability of deformation was minor; therefore, its shrinkage was larger than ordinary concrete. The addition of 20% rubber had the largest change among all of the mix designs, which was consistent with the observations of Shayan and Xu [36]. According to Ahmad Shayan AS3600, the maximum shrinkage of concrete should be lower than 0.075%, which proved the conclusion of Li et al. [37] that the shrinkage of concrete would become higher as more waste tire rubber powder was added.

3.5. Electrical resistance

As shown in Fig. 7, the 56 day surface resistance of the control group was 36.75 kΩ-cm, whereas that of waste tire rubber powder that had been passed through a #30 sieve was within the range of 40.5–44.88 kΩ-cm. The 56 day surface resistance of waste tire rubber powder that had been passed through a #30 sieve was within the range of 37.33–41.55 kΩ-cm, and that of waste tire rubber powder that had been passed through #30 + #50 sieves was within the range of 34.5–37.18 kΩ-cm. This showed that the electrical resistance increased as more powder was added. Generally, the electrical resistance of each mix design was much higher than the lowest 56 day electrical resistance of ordinary concrete, which was 20 kΩ-cm [17]. Additionally, all of the materials were anti-corrosion concrete with good durability. Fig. 8 shows the linear regression relationship of electrical resistance and compressive strength of SCRC with waste tire rubber powder of three different degrees of sieves at four levels of replacement. When the amount of replacement was 0%, the correlation coefficient R^2 was the

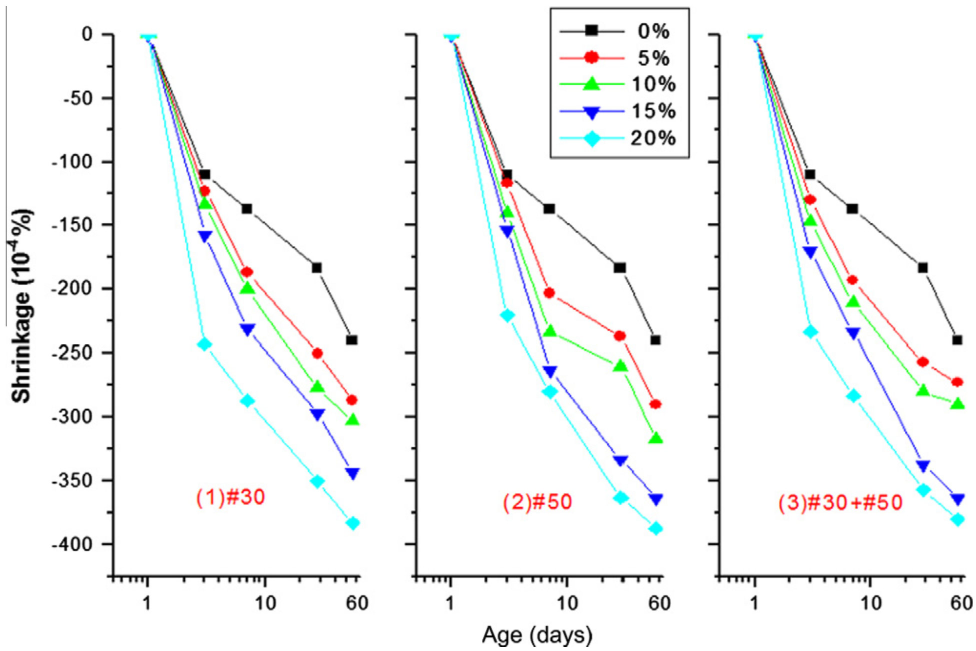

Fig. 6. Shrinkage for SCRC.

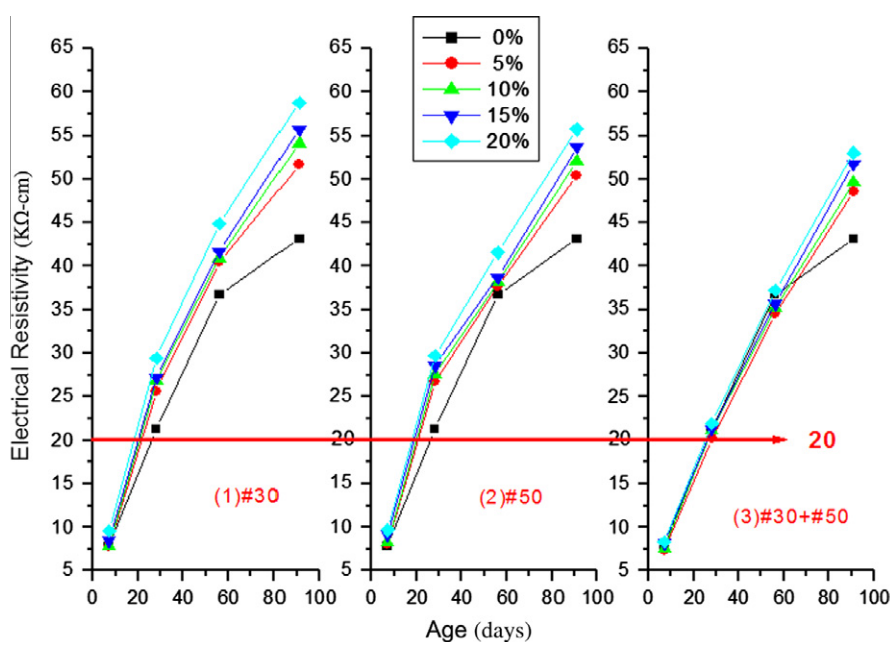

Fig. 7. Electrical resistivity for SCRC.

smallest at 0.793, whereas the others were within 0.870–0.965. The compressive strength and the linear regression values of electrical resistance increased with an increase in the level of replacement, indicating that there was a good linear relationship between the surface resistance and the compressive strength of the concrete.

3.6. Anti-corrosion property

As shown in Fig. 9, the weight loss of the fifth recycling of SCRC of the control group was −3.84%, whereas those with four kinds of waste tire rubber powder that had been passed through #30, #50 and #30 + #50 sieves were within the range of (−2.59–4.11%), (−3.31–6.23%) and (−3.63–4.93%), respectively. With an increase in the time of corrosion, the weight loss of each mix design became larger. Take the fifth recycling as an example; 5% waste tire rubber powder added had the least weight loss, indicating that a 5% addition led to sulfate resistance and good durability. The average weight losses of concretes with waste tire rubber powder that had been passed through a #30 sieve (−3.49%) > #30 + #50 sieve (−4.3%) > #50 sieve (−4.5%); thus, the anti-sulfate corrosion properties of concrete with waste tire rubber powder that had been passed through a #30 sieve at a 5% addition level were the best.

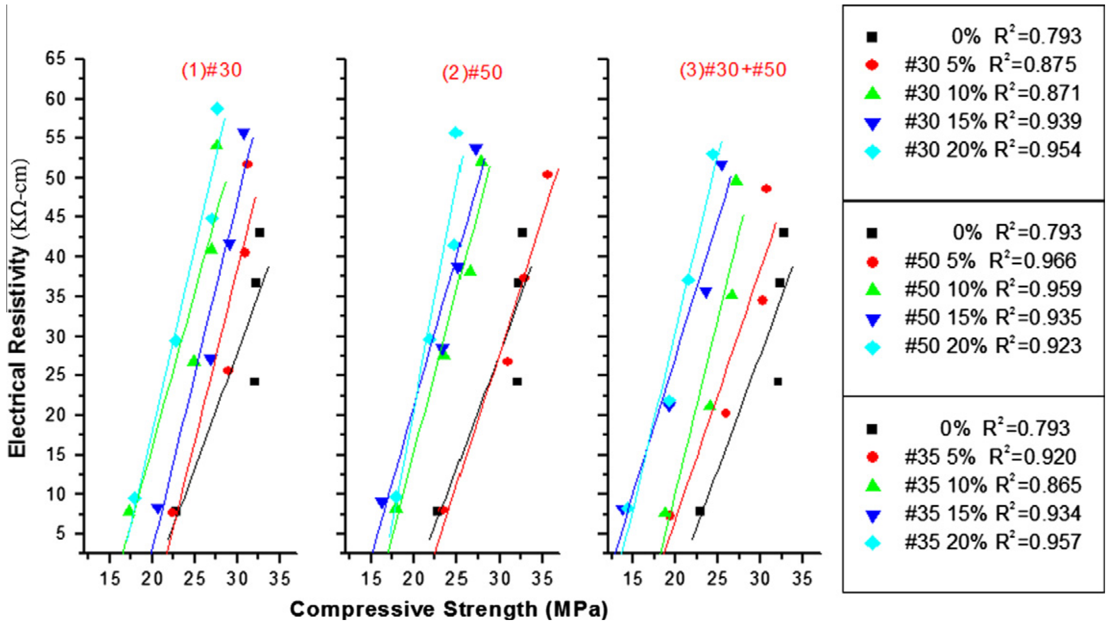

Fig. 8. Relationship between compressive strength and electrical resistivity at different sieved.

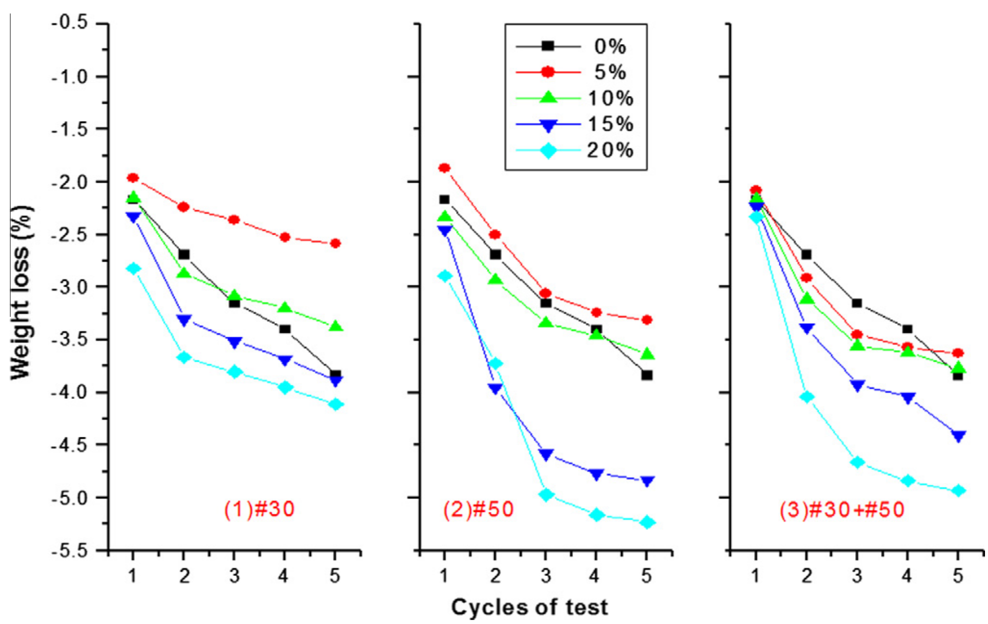

Fig. 9. Weight loss for SCRC immersed in sodium sulfate solution.

4. Conclusions

(1) The compressive strength of SCRC was the best when 5% of the waste tire rubber powder that had been passed through a #50 sieve was added (increased by 1–10%), which meant that adding waste tire rubber powder can meet the safety performance requirements of SCRC. It was not true that when the waste tire rubber powder was finer, the compressive strength of the concrete was higher.

(2) The ultrasonic pulse velocity after 28 days was 4000 m/s when 5% waste tire rubber powder was added, and all of the samples were higher than 4000 m/s. However, if more rubber was added, the ultrasonic pulse velocity decreased to less than 4000 m/s. Because the average waste tire rubber powder that had been passed through a #30 sieve was 6.5% lower than the control group, this indicated that the ultrasonic pulse velocity would decrease with an increase in the amount of waste tire rubber powder.

(3) The shrinkage of concrete with rubber powder was small, but larger than ordinary concrete. When more rubber powder was added, the change in length also increased; a 5% addition of powder led to an increase of 35% in length, and a 20% addition led to an increase of 95%.

(4) The SCRC had relatively high electrical resistance properties, and adding waste tire rubber powder that had been passed through a #30 sieve increased the surface resistance by 17%.

(5) Taking the fifth recycling as an example, 5% waste tire rubber powder had the least weight loss, and adding waste tire rubber powder that had been passed through a #30 sieve led to anti-sulfate corrosion resistance.
(6) The addition of 5% waste tire rubber powder that had been passed through a #50 sieve added was the best level of replacement.

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