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Development of waste tire modified concrete

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Abstract

In this study, waste tire modified concrete was investigated experimentally. Two types of waste tire configurations were evaluated. One was in the form of chips, or particles, and the other was in the form of fibers. For the waste tire chip modified concrete, surface treatment by saturated NaOH solution and physical anchorage by drilling a hole at the center of the chips were also investigated. For the waste tire fiber modified concrete, fibers with various aspect ratios were utilized. A hybrid fiber reinforcement using waste tire fiber and polypropylene (PP) fiber was also investigated. The effect of waste tire resources (car tires or truck tires) on the strength and stiffness was evaluated. A total of 10 batches of concrete, which yielded sixty $\phi 152.4 \times 304.8$ mm cylinders, were prepared. Compressive strength, compressive modulus of elasticity, Poisson's ratio, and split tensile strength tests were conducted on the prepared samples. Ways to further recover the lost strength and stiffness of waste tire modified concrete were discussed based on the test results.

Keywords: Mechanical properties; Composite; Concrete; Fiber reinforcement; Waste tire

1. Introduction

The United States generates approximately 242 million scrap tires per year, representing 1.2 wt.% of all municipal solid waste. The U.S. Environmental Protection Agency estimates that 2–3 billion scrap tires have already accumulated in illegal stockpiles or uncontrolled tire dumps throughout the country, with millions more scattered in ravines, deserts, woods, and empty lots [1–3]. The waste tire stream represents significant environmental, health, and aesthetic problems. Innovative solutions have to be developed to solve this problem.

Highway construction provides a significant market potential for waste tire recycling. Extensive studies have been conducted on crumb rubber modified asphalt [4]. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), Public Law 102-240, mandated on the use of waste tire rubbers in federally funded projects. Starting in 1995, all states were required to pave an equivalent of 5% of their annual federally funded paving projects with tire rubber modified asphalt. In 1998, 20% of the federally funded paving projects were required to use rubber-modified asphalt. However, these requirements have been delayed due to the high cost associated with manufacturing crumb rubbers and the time- and effort-consuming process of producing crumb rubber modified asphalt using the "wet process" [3]. The consumption of waste tires in asphalt pavement construction varies from state to state, with the maximum consumption of 20% [2].

Owing to the problems associated with waste tire modified asphalt, more and more attention has been paid to waste tire modified Portland cement concrete. As opposed to waste tire modified asphalt, which needs the wet process, waste tire modified concrete utilizes the low-cost "dry process", with a portion of aggregates replaced by waste tire rubbers. In addition, the resulting concrete has a very high toughness. This is very desirable because conventional concrete is a brittle material. High toughness suggests that the modified concrete has higher cracking

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and fracture resistance. Eldin and Senouci [1] investigated the strength and toughness of concrete with a portion of aggregates replaced by waste tire chips. They observed that the compressive strength and split tensile strength were reduced, while its toughness and ability to absorb fracture energy were enhanced significantly. They also provided a qualitative explanation of the fracture mechanisms of rubber-filled concrete based on the theory of strength of materials. Topçu [5] investigated the effect of particle size and content of tire rubbers on the mechanical properties of concrete. He found that, although the strength was reduced, the plastic capacity was enhanced significantly. Lee et al. [6] investigated the flexure and impact strength of Styrene–Butadiene–Rubber (SBR) latex modified crumb rubber filled concrete. They found that crumb rubber filled concrete had high flexure and impact strength than conventional Portland cement and latex-modified concretes do. The reason was that the presence of SBR latex formed a thin film at the interface of cement mortar and aggregates, increasing the interfacial bonding strength. However, the increase in initial cost due to the use of SBR latex limited the applicability of the results. Goulias and Ali [7] used nondestructive testing (NDT) to evaluate crumb rubber filled concrete. They attempted to establish a relation correlating the strength and elastic modulus with the parameters from NDT results. Khatib and Bayomy [8] used fine crumb rubber and tire chips to replace a portion of fine or coarse aggregates. They found that the rubber-filled concrete showed a systematic reduction in strength, while its toughness was enhanced. They also proposed a regression equation to estimate the strength of rubber-filled concrete. Segre and Joekes [9] used saturated NaOH solution to treat waste tire rubber powders. They found that NaOH surface treatment increased rubber/cement paste interfacial bonding strength and resulted in an improvement in strength and toughness in waste tire powder modified cement mortar. Hernández-Olivares et al. [10] used crumbed waste tire fibers (average length 12.5 mm) and short polypropylene (PP) fibers (length from 12 to 19 mm) to modify concrete. Based on the picture they provided, it is estimated that the tire fiber thickness was about 0.5 mm. They concluded that the static strength and stiffness of the modified concrete were not reduced significantly.

From the above literature survey, it is seen that waste tire rubber modified concrete is characterized as having high toughness and low strength and stiffness. Various steps have been taken to improve the strength and stiffness of waste tire modified concrete. Among them, two ways are of particular interest. One is the surface treatment of waste tire powders using NaOH and the other is using thin waste tire fibers. However, preparing waste tire powders and thin tire fibers is time, effort, and money consuming. Sometimes, the cost may be so high that it cannot be justified by its gain in performance. Because larger sized chips or fibers are very easy to produce, it is expected that the cost of larger sized chip or fiber-modified concrete will be very low. However, it is not clear if larger sized fibers or NaOH-treated chips work or not. Further investigations are needed.

The objective of this study was to evaluate the feasibility and performance of waste tire modified concrete using larger sized fibers and NaOH-treated chips. Other aspects that may affect the performance of modified concrete, including physical anchorage, fiber aspect ratio, tire resources, and hybrid fiber reinforcement, were also investigated. Ways to further improve the strength and stiffness of the modified concrete were proposed based on the test results.

2. Experiments

2.1. Raw materials and specimen preparations

Type I Portland cement, gravel, natural sand, water, and DARAVAIR 1000 were used to prepare the concrete. Concrete with 40 MPa compressive strength was designed as the control mix. The mix design followed ACI Standard 211.1 (Standard 1991). In preparing the rubberized concrete samples, 15 vol.% of coarse aggregate (gravel) was replaced by waste tire chips or fibers. The mix ratio by weight for the control concrete was cement/water/gravel/sand/admixture = 1:0.50:3.50:1.88:0.001; the mix ratio by weight for rubberized concrete was cement/water/gravel/waste tire/sand/admixture = 1:0.50:3.33:0.17:1.88:0.001. The concrete was mixed, cast, demolded, and cured for 28 days in a controlled environment. Slump and air content tests were also conducted on the fresh concrete to estimate the workability of the designed mix.

Two types of waste tire configurations were investigated. One was waste tire chips or particles; the other was waste tire fibers. The waste tire chips used came from mixed car tires and truck tires, approximately in a ratio of 1:1, with the steel belt wires included. They were obtained using a shredder. The chips were almost square shaped, with length about 25.4 mm, width about 25.4 mm, and thickness about 5 mm. The chips were divided into three subgroups. The first subgroup was used as a control. The second subgroup was surface treated, conducted using analytical grade NaOH. Saturated NaOH solution was prepared. Waste tire chips were put into the solution in a ceramic container for half an hour while stirring. After that, the treated waste tire chips were rinsed using drinking water. To increase the interfacial bonding between the chips and the cement paste matrix, physical anchorage was used for the third subgroup. This was achieved by drilling a hole with a diameter of 5 mm at the center of each chip. Fig. 1(a) shows the chip used; Fig. 1(b) shows that the chips were immersed in saturated NaOH solution; and Fig. 1(c) shows that the central hole in the chip was filled with cement paste.

The waste tire fibers were obtained by mechanical cutting. The fibers used were either from mixed truck and

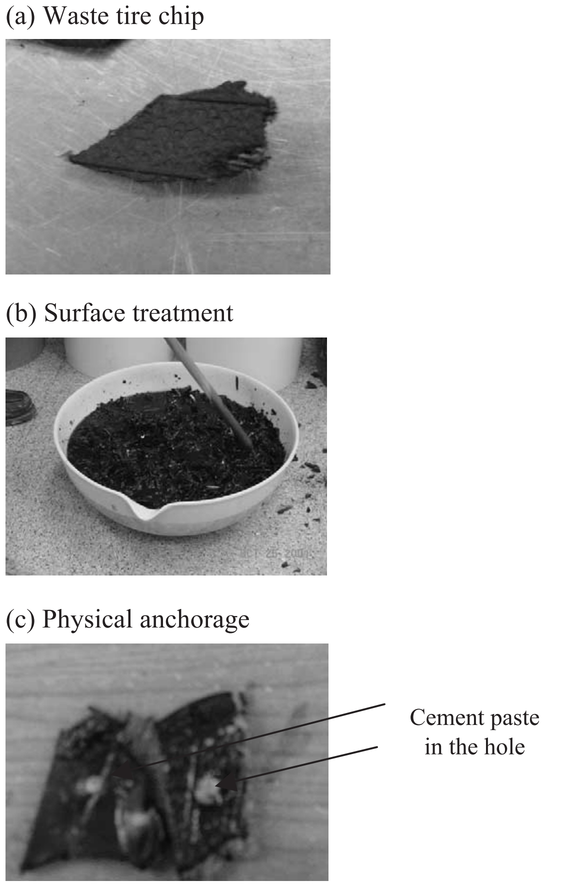


Fig. 1. Various chips used.

car tires, approximately in a ratio of 1:1, or from car tires only. Some fibers had steel belt wires and some did not. This was to investigate the effect of fiber stiffness on the strength of the modified concrete. The cross-section of the fibers was almost a square, with a thickness of about 5 mm. To investigate the effect of fiber aspect ratio on the strength and stiffness of the modified concrete, three fiber lengths, 25.4, 50.8, and 76.2 mm, were used. As PP fibers have been widely used in reinforcing concrete, hybrid waste tire fiber and PP fiber modified concrete was also prepared. Each PP fiber was 50.8 mm long and contained many filaments. The PP fiber content was 0.1 vol.% of concrete. The nominal physical/mechanical properties of waste tire rubbers and PP fibers are shown in Table 1. Fig. 2 shows the waste tire and PP fibers in concrete.

Table 1
Nominal physical/mechanical properties of waste tire rubber and PP fiber

Material	Density (g/cm^3)	Young's modulus (MPa)	Tensile strength (MPa)
Waste tire rubber	0.84	2.0 at 100% strain	28
Polypropylene	0.91	3500	620

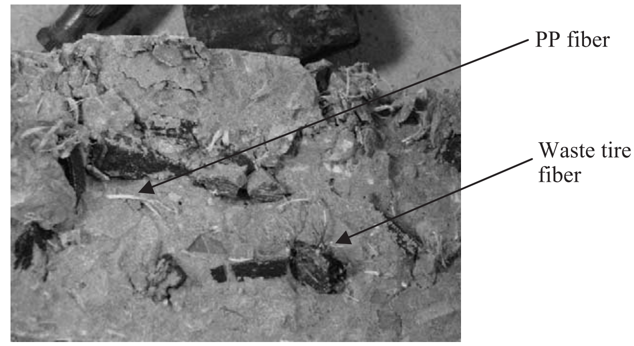


Fig. 2. Waste tire fibers and PP fibers in concrete.

A total of 10 batches of concrete was prepared, which yielded 60 cylinders with a diameter 152.4 mm and a height 304.8 mm (each batch contained six samples). The details of waste tire chips or fibers used in each batch of concrete are shown in Table 2.

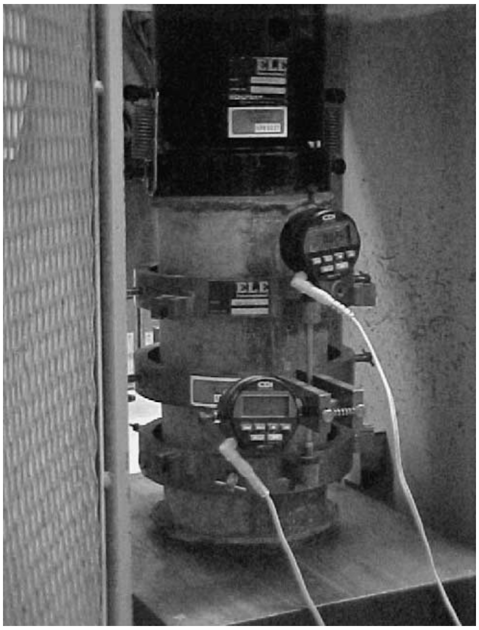
2.2. Experiment

For each batch of concrete, three cylinders were used to conduct compressive modulus, compressive strength, and Poisson's ratio tests. The remaining three samples were used to conduct split tensile strength tests. The compression tests were conducted per ASTM C 39 Standard, and the indirect tensile (split tensile) strength test was conducted per ASTM C 496 Standard. A MTS machine was used to conduct the specified test. Fig. 3(a) shows a

Table 2
Test matrix

Batch No.	Description	Rubber length (mm)	Rubber width (mm)	Rubber thickness (mm)
1	Control	–	–	–
2	Mixed tire chips with steel wires	25.4	25.4	5
3	Mixed tire chips with steel wires and surface treated by NaOH	25.4	25.4	5
4	Mixed tire chips with steel wires and with a hole at the center	25.4	25.4	5
5	Car tire fibers	25.4	5	5
6	without steel wires	50.8	5	5
7		76.2	5	5
8	Car tire fibers with steel wires	50.8	5	5
9	Mixed tire fibers with steel wires	50.8	5	5
10	Car tire fibers without steel wires and with 0.1 vol.% of PP fibers (length 50.8 mm)	50.8	5	5

(a) Compression test



(b) Split tensile test

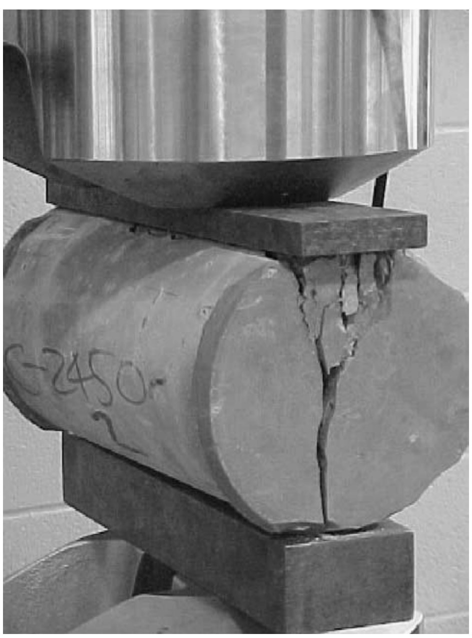


Fig. 3. Compression and split tensile tests.

sample under compressive test, and Fig. 3(b) shows a sample under split tensile test.

3. Results and discussion

The test results of the averaged compressive strength, split tensile strength, modulus of elasticity, Poisson's ratio, slump, and air content for each batch of concrete are summarized in Table 3. From Table 3, the following analyses are conducted.

Table 3
Test results

Batch No.	Compressive strength (MPa)	Split tensile strength (MPa)	Modulus of elasticity (MPa)	Poisson's ratio	Slump (cm)	Air content (%)
1	39.08	3.11	34.72	0.23	14.7	4.5
2	22.33	2.29	28.89	0.22	14.4	4.1
3	23.23	2.19	28.88	0.21	14.3	5.0
4	22.89	2.38	28.69	0.22	14.2	4.6
5	22.16	2.17	26.93	0.23	14.6	4.8
6	20.48	2.15	28.59	0.25	15.2	5.0
7	20.82	1.99	28.39	0.24	14.0	4.7
8	22.83	2.41	30.40	0.25	14.8	4.6
9	25.14	2.62	31.19	0.21	15.2	4.9
10	25.60	2.69	31.96	0.23	14.8	5.0

3.1. Effect of waste tire rubbers on the workability of the modified concrete

For concrete, slump and air content are the parameters related to concrete workability. From Table 3, the slump and air content of the modified concrete (Batches 2–9) are very close to that of the control concrete (Batch 1). This means that with 15% replacement of coarse aggregates by waste tire rubbers, the effect of waste tire rubbers on the workability of the modified concrete is minimal, regardless of chips or fibers. The modified concrete can be mixed, cast, and compacted using the equipment for conventional concrete.

3.2. Effect of waste tire rubbers on the toughness of the modified concrete

The introduction of waste tire rubbers into concrete greatly enhances the toughness of the modified concrete, regardless of chips or fibers. Fig. 4 shows typical load–

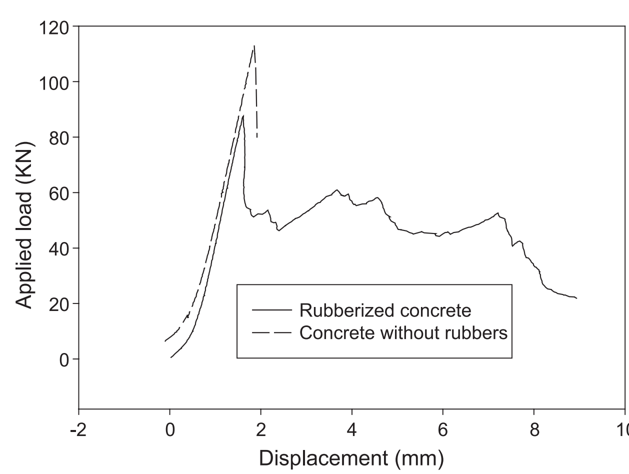


Fig. 4. Load–displacement curves of control concrete and rubberized concrete samples under split tensile test.

displacement curves of both control and waste tire fiber modified concrete columns from Batch 9 during split tensile testing. From Fig. 4, the energy absorbed by the rubberized concrete (the area between the load–displacement curve and the abscissa) is much larger than that by the control concrete; thus, the toughness of the rubberized concrete is increased considerably. This means that the rubberized concrete has a significant capability in absorbing dynamic load and in resisting crack propagation. The enhanced toughness can also be demonstrated by the effort required to fully open the samples. For the control concrete, the split tensile tested samples can be easily broken into two halves without using any tools. However, a wedge and a hammer were used to fully open the modified concrete, as shown in Fig. 5. It was also observed during the tests that it was more difficult to fully open a waste tire fiber modified concrete column than to fully open a waste tire chip modified concrete. This suggests that waste tire fiber modified concrete has a higher toughness than waste tire chip modified concrete does.

3.3. Effect of waste tire rubbers on the strength and stiffness of the modified concrete

From Table 3, the strength and stiffness of waste tire rubber modified concrete are lower than those of the control concrete, regardless of chips or fibers. This is understandable because waste tire rubbers are much softer than the concrete matrix. Soft inclusions act as stress concentrators in the composite. The stress concentration causes debonding of the rubbers from the concrete matrix. It also causes microcracking of the concrete matrix. Subjected to compressive loads, the debonded rubbers act as voids in the modified concrete, which inevitably reduce the compressive strength and modulus of elasticity of the modified concrete. Subjected to tensile loads, the debonded chips or fibers transfer the applied load through interfacial frictional forces only. Compared with interfacial bonding strength, the interfacial frictional force is very small and easy to overcome, resulting in lower split tensile strength of the modified concrete. Considering that the microcracks in the concrete matrix also reduce the strength and stiffness of the modified concrete, it cannot be avoided that the strength and stiffness of the modified concrete are decreased. To reduce the strength and stiffness loss, enhancing the interfacial bonding between the waste tire rubber and the concrete matrix and reducing the stress concentration will be effective ways.

Fig. 5. Open a split tensile tested sample of rubberized concrete using a wedge and a hammer.

3.4. Fibers versus chips

The difference between Batches 2 and 9 is that Batch 2 utilized chips and Batch 9 employed fibers. From Table 3, the strength and stiffness of Batch 9 are higher than those of Batch 2. Batches 3 and 4 used either surface treatment or physical anchorage; their strength and stiffness are still lower than those of Batch 9. Considering that waste tire fiber modified concrete has a higher toughness than that of waste tire chip modified concrete, as discussed in Section 3.2, it is concluded that waste tire fibers perform better than waste tire chips do. Waste tires should be used in the form of fibers instead of chips. A possible reason for the difference between chips and fibers may be due to the difference between their load transfer capabilities. Once debonded from the concrete matrix, chips do not have enough length to transfer the applied load through interfacial frictional force, while fibers have longer length to transfer the applied load, resulting in a higher strength. In industry, waste tire chips are produced by shredders. However, there is currently no special equipment to cut waste tire fibers. Further studies are needed to develop suitable equipment.

3.5. Effect of surface treatment on the strength and stiffness of the modified concrete

Batch 3 was surface treated using saturated NaOH solution. Comparing the strength and stiffness of Batch 3 with those of Batch 2, it is found that the results from Batch 3 are nearly the same as those in Batch 2. Unless there are some innovative methods available, the results from this study suggest that surface treatment does not work for waste tire chips. It is noted that a previous study by others [9] concluded that NaOH surface treatment improved the strength and stiffness of the modified mortar. The difference between the previous results and the results from this study may be because they used waste tire powders. The big surface area of powders insures that more surface contact occurs and more possible chemical reaction happens at the powder surface. Consequently, the mechanical properties of the modified mortar were improved. In summary, although NaOH surface treatment worked for small-sized waste tire powders, it fails to work for larger sized waste tire chips. It is noted that waste tire powders are much more expensive than chips, probably in a ratio of 10:1. Extensive application of powders should be limited.

3.6. Effect of physical anchorage on the strength and stiffness of the modified concrete

In Batch 4, a 5-mm-diameter hole was drilled for each chip. The idea was that some cement paste would be able to pass through the hole and form a small column during mixing. The small cement paste column would be connected to the surrounding concrete, and thus, physical anchorage could be formed. Comparing Batch 4 with Batch 2, only a slight improvement in strength and stiffness was achieved in Batch 4. Observing the tested samples, it is found that only a small number of chips had the small cement paste column, as shown in Fig. 6. A majority of chips failed to form the anchorage. This may be why the improvement in strength and stiffness is insignificant. A careful examination shows that the drilled holes in a large number of chips have already closed before mixing due to the rebound of the rubber. Thus, it was impossible to develop the physical anchorage. It is expected that larger sized or punched holes would work better.

3.7. Effect of fiber aspect ratio on the strength and stiffness of the modified concrete

Batches 5, 6, and 7 utilized larger and larger fiber aspect ratios. Comparing Batch 5 with Batches 6 and 7, it is found that the strength decreases as the fiber length increases. This is opposite to common knowledge or wisdom. An in-depth analysis shows that the reason for this abnormal observation is due to fiber entangling and fiber clustering formed during vibrating and compacting of fresh concrete. For Batches 6 and 7, particularly for Batch 7, the fibers formed clusters and were not uniformly dispersed into the concrete. Therefore, although longer fibers are easy to cut and have a potential to offer higher strength, the fiber length has to be restricted within a certain extent. Otherwise, clustering cannot be avoided. Based on this study, it is proposed that the fiber length should be no more than 50.8 mm. To increase the fiber aspect ratio, appropriate cutting tools have to be developed to cut thinner fibers.

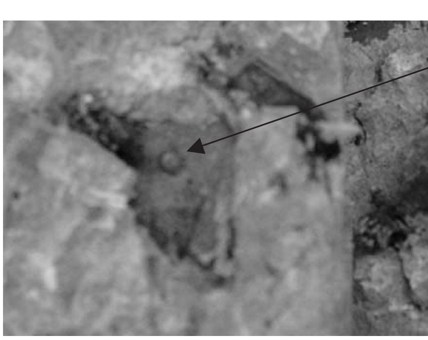


Fig. 6. A small cement paste column left by a drilled chip.

3.8. Effect of fiber stiffness on the strength and stiffness of the modified concrete

Batches 6, 8, and 9 used fibers with the same dimensions. The difference among them is their stiffness. Batch 6 used car tires without steel belt wires, while Batch 8 had steel belt wires. For Batch 9, it not only had steel belt wires but also used mixed truck and car tires. Because truck tires are stiffer than car tires, the stiffness, in a descending sequence, for the fibers used in the three batches of concrete is that the stiffness in Batch 9 is greater than that in Batch 8, which is greater than the stiffness in Batch 6. From Table 3, the strength and stiffness of Batch 9 are higher than that of Batch 8 and are much higher than that of Batch 6. This means that the stiffness of the waste tire fibers plays an important role in developing the strength and stiffness of the rubberized concrete. Increasing the stiffness of the waste tire fibers can increase the strength and stiffness of the rubberized concrete. Therefore, using truck tire fibers is better than using car tire fibers and fibers with steel belt wires are better than fibers without steel belt wires. Because cutting stiffer tires requires higher energy, a balance needs to be sought between the performance and the cost of the modified concrete. More studies are needed to establish an optimal balance.

3.9. Effect of hybrid fiber reinforcement on the strength and stiffness of the modified concrete

Batches 10 and 6 employed the same type of waste tire fibers. The difference between them is that Batch 10 contained 0.1 vol.% of PP fibers, while Batch 6 did not. From Table 3, the strength and stiffness of Batch 10 are considerably higher than those of Batch 6. This means that a small amount of PP fibers can effectively increase the strength and stiffness of the modified concrete. It is expected that the hybrid fiber reinforcement have a potential to achieve the same, or even higher, strength and stiffness than the control concrete as the PP fiber content increases. It is interesting to note that the hybrid fiber reinforcement not only increases the strength and stiffness but also retains the high toughness of waste tire fiber modified concrete. A possible reason for this may be that waste tire fibers mainly contribute to toughness, and PP fibers are mainly responsible for strength. Therefore, it is expected that a high-strength and high-toughness concrete may be achieved by hybrid waste tire fiber and PP fiber reinforcement. Further studies are needed to fully display the benefit of the hybrid fiber reinforcement.

It is noted that a similar concept has been used by other researchers [10]. They also used a similar amount of waste tire and PP fibers. However, from the pictures presented in their paper, it is estimated that their waste tire fibers were very thin, approximately 0.5 mm thick. For such thin fibers, a considerable energy is required to cut from the waste tires, resulting in higher cost. In this present study, much thicker waste tire fibers (5 mm thick) were used, which means lower cost. From the data presented by the previous researchers, it is seen that, compared with their control concrete, the compressive strength was reduced by 27.5% and the split tensile strength was reduced by 11.8%. From Table 3, the corresponding numbers became 35.6% and 13.5%, respectively. Obviously, using thinner fibers is better than using thicker fibers in modified concrete performance. However, the difference is not very significant, particularly for the split tensile strength (11.8% vs. 13.5% reduction). Again, a balance must be sought between the performance and the cost of the modified concrete. A more refined study is needed to find the optimal fiber thickness.

4. Conclusion

A comprehensive test program was conducted in this study to develop waste tire modified concrete. A total of 10 batches of concrete with sixty $\phi 152.4 \times 304.8$ mm cylinders were prepared and tested. Various test variables have been experimentally investigated. Based on the test and analysis results, the following preliminary conclusions are obtained:

(1) Fibers perform better than chips do. Although thinner fibers perform better than thicker fibers do, the effect is not very significant. Further studies are needed to develop suitable cutting machines and optimal fiber thickness.
(2) Unless some new methods are available, NaOH surface treatment does not work for larger sized tire chips.
(3) Using physical anchorage has some effect. Further efforts will be geared toward enlarging the hole size and insuring that the hole be through the chip thickness entirely.
(4) Longer fibers tend to entangle. It is suggested that fiber length be restricted to less than 50 mm.
(5) Steel belt wires in waste tires have a positive effect on increasing the strength of rubberized concrete. Truck tires perform better than car tires do.
(6) Hybrid fiber reinforcement has a potential to produce higher strength and higher toughness concrete. More PP fibers are needed to fully recover the lost strength.

Acknowledgements

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