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Utilization of waste vehicle tires in concrete and its effect on the corrosion behavior of reinforcing steels

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Abstract: The mechanical and physical properties of concrete specimens obtained from replacing natural coarse aggregate with waste vehicle rubber tires at levels of 2vol%, 5vol%, 7vol%, and 10vol% were studied, and the corrosion behavior of reinforcing steels was investigated in these specimens. Corrosion rates were determined by measuring the galvanic current between steel-reinforced concrete specimens both with and without chloride addition. The change in electrode potential of reinforcing steels in these concrete specimens was measured daily for a period of 60 d in accordance with the testing method in ASTM C876. The results show that the use of waste vehicle tires in concrete instead of coarse aggregate decreases the mechanical strength of the specimens, and increases the corrosion rates of the reinforcing steels embedded in the concretes.

Keywords: vehicle tire; concrete; corrosion; reinforcing steel; waste reuse

1. Introduction

Currently, solid waste is one of the most important issues in the world. Most of the solid waste is produced by polymers, such as water bottle, polymer bags, packing materials, home tools, and vehicle tires. Vehicle tires have an exceptional place in solid waste. Compared with other polymer materials, because of long-time degradation in nature, vehicle tires lead to much more problems in terms of environmental pollution and human health. In order to prevent this problem, vehicle tires should be reused in economy and valued in new usage areas as addition agents.

Waste tires result in significant environmental, health, and aesthetic problems. Innovative solutions have to be developed to solve these problems. Several studies have been carried out to reuse waste tires as rubber and plastic products, or as fuels for cement kilns, as well as in concrete and asphalt technologies.

Although concrete is the most commonly used construction material, it cannot meet the desired demand in buildings because of its high unit weight, low saturation, low resilience, and inadequate sound insulation [1-2]. Various studies have been conducted in recent years to improve these properties of concrete. A limited number of studies have been conducted on the use of waste vehicle tires in conventional concrete mixtures as aggregate.

Li *et al.* [3] investigated the development of waste tire modified concrete. They used vehicle tires as the addition to concrete in the form of fibers and chips in an attempt to replace the coarse aggregate by volume. They reported that fibers yielded better results compared to chips. Khatib and Bayomy [4] used rubber aggregate in concrete; based on the experiments, the unit weight of the concrete decreased whereas the rubber amount increased. Olivares *et al.* [5] used crumbed waste tire fibers (with an average length of 12.5 mm) and short polypropylene fibers (with a length of 12-19 mm) to modify concrete, and the tire fiber thickness was estimated to be about 0.5 mm. They concluded that the addition of crumbed tire rubber up to 5vol% in a cement matrix did not imply a significant variation in mechanical features of concrete. Topçu [6] investigated the effects of particle size and tire rubber content on the mechanical properties of concrete, and found that the plastic capacity was significantly enhanced while the strength was reduced.

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Güneyisi *et al.* [7] produced concretes with silica fume content and 2.5vol%, 5vol%, 10vol%, 15vol%, 25vol%, and 50vol% rubber aggregate in several sizes, respectively, and observed a decrease in unit weight of the concrete in accordance with an increase in rubber amount. Furthermore, it was discovered that there were large reductions in strength and modulus when the rubber content was increased. However, the addition of silica fume into the matrix improved the mechanical properties of the rubberized concrete and reduced the rate of strength loss.

The literatures on the use of tire rubber particles in cement-based materials focus on the use of tire rubber as aggregate in concrete, whereas less attention has been given to its durability until now.

The mechanical and physical properties of concrete specimens obtained by replacing natural coarse aggregate with waste vehicle tires at levels of 2vol%, 5vol%, 7vol%, and 10vol% were investigated in this paper, and the corrosion behavior of reinforcing steels embedded in these specimens was studied.

2. Materials and methods

A total of five series of adjacent concrete specimens, including the control specimen, were prepared to examine the effect of vehicle tires added to concrete by replacing natural coarse aggregate at levels of 2vol%, 5vol%, 7vol%, and 10vol% on the corrosion of reinforcing steels. A total of 25 pieces of 100 mm×100 mm×200 mm concrete blocks in adjacent position, including five samples from each serial, were obtained. The change in corrosion rate of reinforcing steels embedded in concrete was determined based on the galvanic current method (GCM).

GCM is based on the principle of measuring the galvanic current between electrodes embedded in an electrolyte with different features by means of a sensitive ammeter. Jang and Iwasaki implemented this method in two different ways [8]. First, out of two reinforcing steels, one was immersed in a solution containing concrete cracks including chloride, the other was immersed in a solution without chloride. The solutions in two different vessels with concrete particles with and without NaCl were made to come into contact with each other with a saturated ammonium nitrate salt bridge. Reinforcing steels were connected to each other with a cable, and the amount of flow passing through the cells was read with a zero resistant ammeter. The same experiment was also performed by using two concrete blocks instead of concrete cracks. In this case, a curtain was placed between the concrete blocks. The concrete blocks were connected to each other with a salt bridge, and the galvanic current between reinforcing steels was read with a zero resistant ammeter. By using GCM, Asan and Yalçın [9] examined the effects of chloride ions, acetate ions, and fly ash on the corrosion of steel in the concrete. Keleştemur and Yıldız [10] examined the effects of different NaCl concentrations on the corrosion of steels in concrete produced by adding styrofoam.

In this paper, 3wt% NaCl was added into the mix water on one side of the adjacent concrete blocks to create corrosive environment. It was considered in this study that galvanic current would occur between the electrodes embedded in concrete with tire addition and with or without chloride, and the change in corrosion rate was determined by GCM. Moreover, the electrode potentials of reinforcing steels embedded in these concrete specimens were measured daily for a period of 60 d in accordance with the testing method in ASTM C876 [11] to determine whether reinforcing steels were active or passive. These measurements were presented in graphs.

2.1. Preparation of electrodes

As an electrode, the SAE1010 steel bar produced by Ereğli Iron and Steel Factories in Turkey, which was the fundamental construction material of the construction industry, was selected for the study. The as-received material was in the form of a hot-rolled bar of 12 mm in diameter. The chemical composition of SAE1010 is presented in Table 1.

Table 1. Chemical composition of the steel wt%

C	Mn	Si	P	S	Fe
0.170	0.250	0.050	0.005	0.050	Bal.

Fifty pieces of steel bars of 120 mm in length were cut out from the as-received material, and their surfaces were mechanically cleaned. The sample surfaces were polished with 1200 mesh sandpaper. The polished surfaces were cleaned with ethyl alcohol. Then, 10-cm^2 surface areas were kept open at the tips of electrodes, which would be embedded in the concrete. Screw thread was machined in the other ends of the steel electrodes, and cables were connected to these ends to make easier measurements during the experiment. The remaining sections of the electrodes were protected against external effects by covering them firstly with epoxy resin, and then with polyethylene.

2.2. Preparation of concrete specimens for corrosion experiments

Cubic concrete specimens (100 mm×100 mm×100 mm) in adjacent form were prepared for corrosion experiments. Steel electrodes prepared in advance were embedded in these adjacent concrete blocks as demonstrated in Fig. 1. The black areas on the electrodes in Fig. 1 indicate that the areas are kept under protection.

The specimens were kept in molds for 24 h and then unmolded. In order to prevent the specimens from losing their conductive nature and for standardization purposes, they were cured at a relative humidity of 90% and 20±2°C for 60 d.

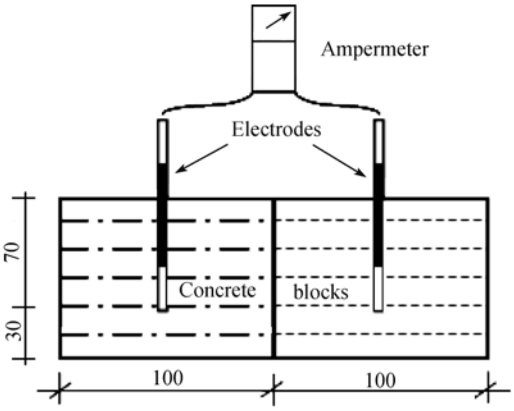

Fig. 1. Schematic demonstration of the electrodes embedded in adjacent concrete blocks (unit: mm).

2.3. Composition of concrete specimens prepared for corrosion experiments

ASTM C150 Type I Portland cement was used to prepare all concrete specimens included in the experiments within the scope of the study. The chemical composition of this cement is presented in Table 2. The density of the cement used in the concrete mixture is 3.1 g/cm^3. Tap water was used as the mix water while the concrete blocks were prepared.

A total of 25 pieces of concrete block specimens were prepared for the experimental study on corrosion. The compositions of the adjacent concrete specimens are presented in Table 3.

Waste vehicle tires used in the study were selected from waste tires emerging during the process of tire covering. The tires obtained by cutting with a special cutting device were sieved through 4.25 to 9.50 mm sieves in accordance with the ASTM C136 [12] standard to be used in the concrete. Then, these tires were used to replace natural coarse aggregates in different ratios to prepare concrete samples. The average length and diameter of coarse tire aggregates were determined by the measurements of 100 units of specimens through a caliper. The average length and diameter of the tires were found to be 21.75 and 3.63 mm, respectively. Moreover, the density, the loose bulk density, and the closed packing density of the tires used in the study were determined to be 0.91, 0.36, and 0.46 g/cm^3, respectively. The tires used in the experiments are displayed in Fig. 2.

The aggregate was of good-quality river gravel and sand commonly used in concrete production (the maximum grain size of the aggregate was 8 mm). The aggregate has a density of 2.56 g/cm^3 and a water absorption of 3.2%. Aggregate granulometry used in the mixes is shown in Table 4. Table 5 presents the mixture proportion of the concrete specimens prepared for the corrosion experiments in five groups.

Table 2. Chemical composition of the cement **wt%**

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl^-	Loss of ignition (LOI)	Unknown
22.05	5.40	3.18	63.07	2.21	2.20	0.009	1.29	1.80

Table 3. Composition of the adjacent concrete specimens

Specimen	Left block	Right block
C	Normal concrete	Normal concrete+6.9 kg/m^3 Cl^-
T2	Normal concrete+2vol% tire	Normal concrete+2vol% tire+6.9 kg/m^3 Cl^-
T5	Normal concrete+5vol% tire	Normal concrete+5vol% tire+6.9 kg/m^3 Cl^-
T7	Normal concrete+7vol% tire	Normal concrete+7vol% tire+6.9 kg/m^3 Cl^-
T10	Normal concrete+10vol% tire	Normal concrete+10vol% tire+6.9 kg/m^3 Cl^-

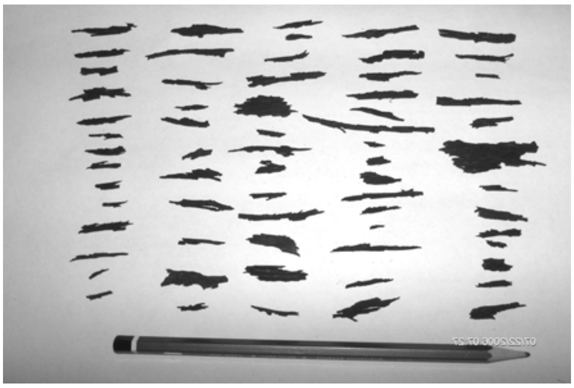

Fig. 2. Waste tire fibers used in the study.

Table 4. Aggregate granulometry used in the mixes

Sieve size / mm	8	4	2	1	0.50	0.25
Passing / %	100	65	48	33	19	7

Table 5. Mixture proportion of specimens kg/m^3

Constitution	C	T2	T5	T7	T10
Cement	418.0	418.0	418.0	418.0	418.0
Sand (0-4 mm)	993.3	993.3	993.3	993.3	993.3
Gravel (4-8 mm)	535.0	504.5	458.6	428.1	382.2
Water	230.0	230.0	230.0	230.0	230.0
Tire	0.0	10.9	27.2	38.0	54.3
NaCl	6.9	6.9	6.9	6.9	6.9

2.4. Hardened concrete experiments

The corrosion behaviors of the concrete specimens consisting of waste vehicle tires at various proportions as well as their mechanical and physical properties such as unit weight, compressive strength, splitting tensile strength, and ultrasonic pulse velocity were investigated according to ASTM C138 [13], ASTM C39 [14], ASTM C496 [15], and ASTM C597 [16], respectively. Moreover, porosity and sorptivity measurements were also conducted on the concrete specimens. The data were interpreted together with the corrosion rate of steels embedded in the rubberized concrete specimens.

Porosity measurements were carried out on 100 mm cube specimens. The specimens were dried in the oven at about 50°C until constant mass was achieved, and the specimens were then placed for at least 3 h in desiccators under vacuum. Finally, they were filled with de-aired and distilled water. This method for measuring the porosity has been reported previously [17-20]. The porosity is calculated by the following equation:

$$P = \frac{W_{\text{sat}} - W_{\text{dry}}}{W_{\text{sat}} - W_{\text{wat}}} \times 100\% \tag{1}$$

where P is the vacuum saturation porosity, %; W_{sat} the weight in air of the saturated specimen; W_{wat} the weight in water of the saturated specimen; and W_{dry} the weight of the oven-dried specimen.

Three test specimens for absorptivity measurement were prepared for each mixture. Measurements of capillary absorption were carried out using the specimens pre-conditioned in the oven at about 50°C until constant mass was achieved. Then, the concrete specimens were cooled down to room temperature. As shown in Fig. 3, the test specimens were exposed to water on one face by placing them on a pan. The water level in the pan was maintained at about 5 mm above the base of the specimens during the experiment. The lower areas on the sides of the specimens were coated with paraffin to achieve unidirectional flow. At certain times, the mass of the specimens was measured using a balance. The amount of water absorbed was calculated and normalized with respect to the cross section of the specimen exposed to the water at different periods of time such as 0, 5, 10, 20, 30, 60, 180, 360, and 1440 min, respectively. The capillary absorption coefficient (k) is obtained by using the following equation:

$$\frac{Q}{A} = k\sqrt{t} \tag{2}$$

where Q is the amount of water absorbed, cm^3; A the cross-section of the specimen in contact with water, cm^2; t the time, s; and k the absorptivity coefficient of the specimen, cm·s$^{-1/2}$. To determine the absorptivity coefficient, Q/A was plotted against the square root of time ($\sqrt{t}$), and k was calculated from the slope of the linear relation between Q/A and $\sqrt{t}$. This method for measuring the capillary absorption of the concrete specimens was also used in Refs. [17-18, 21-22].

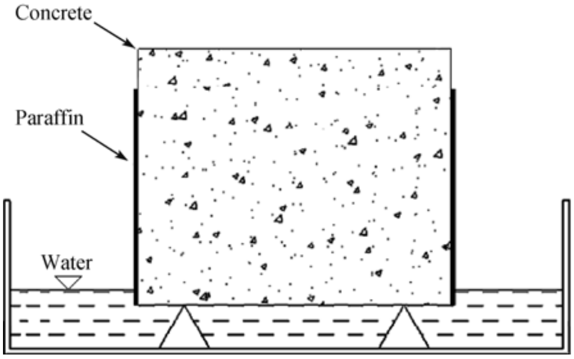

Fig. 3. Measurement of water capillary sorption.

2.5. Corrosion potential measurements

The corrosion potentials of reinforcing steel embedded in the rubberized concrete specimens were measured daily for a period of 60 d in accordance with the testing method in ASTM C876 [11]. A saturated copper/copper sulfate electrode (CSE) was used as the reference electrode, and a high impedance voltmeter was used as the measurement device for corrosion potential measurements. Changes in corrosion potential *vs.* time were indicated in graphs in order to determine whether the steel was active or passive.

Recommendations on the evaluation of potential measurement results in the ASTM C876 experiment method are stated in Table 6 [23-25].

Table 6. Estimation of corrosion probability determined by the half-cell potential test

Potential / mV *vs.* CSE	Probability of the presence of active corrosion
>–200	The probability of corrosion is very low
–200- –350	Uncertain
<–350	The probability of corrosion is very high

2.6. Galvanic current measurements

In this experiment, the galvanic current values of the specimens were measured daily for a period of 60 d. Relative corrosion rates were determined by dividing the galvanic current passing through the galvanic cell to the surface area of the electrode. A high impedance voltmeter was employed as the measurement device for galvanic current measurements.

3. Results and discussion

3.1. Results of mechanical and physical experiments conducted on hardened concrete

The data obtained through mechanical and physical experiments conducted on the concrete specimens are presented in Table 7.

Table 7. Results of mechanical and physical tests of the specimens

Property	Specimen				
	C	T2	T5	T7	T10
Unit weight / (kg·m^{-3})	2260	2230	2190	2160	2120
Compressive strength / (N·mm^{-2})	45.7	44.6	42.5	40.8	37.3
Splitting tensile strength / (N·mm^{-2})	4.19	4.03	3.74	3.51	3.14
Ultrasonic pulse velocity / (km·s^{-1})	4.87	4.31	3.75	3.46	3.13
Porosity / %	9.85	11.34	13.39	15.10	17.15
Sorptivity coefficient / (10^{-3} cm·s$^{-1/2}$)	0.94	1.05	1.18	1.29	1.45

The results in Table 7 suggest a systematic reduction in unit weight but an increase in vehicle tire content of the concretes. This is an expected situation. Similar relations have also been reported by Khatib and Bayomy [4]. Because of the low density of rubber particles, the unit weight of mixtures containing rubber decreases while the rubber content increases. Moreover, the increase in rubber content leads to an increase in air content, which, in turn, reduces the unit weight of the mixtures [4]. In addition, the increase in tire ratio results in decreases in compressive strength and tensile strength. Moreover, the ultrasonic pulse velocity of the specimens experiences a decrease. This decrease in ultrasonic pulse velocity is based on the high sound resistance of tires. The strength reduction observed in the rubberized concrete when the rubber content is increased may be attributed to two reasons as reported by Khatib and Bayomy [4]. The first reason is that the rubber particles are much softer (elastically deformable) than the surrounding cement paste and cracks are initiated quickly around the rubber particles in the mix, which accelerates the failure of the rubber-cement matrix. The other one is that soft rubber particles behave as voids in the concrete matrix due to the lack of adhesion between the rubber particles and the paste. The reduction in strength of the rubberized concrete used in the study is based on the lack of adhesion between the rubber particles and concrete. The lack of adhesion results in a void between the concrete and tire particles. These voids decrease the strength of rubberized concrete. This is presented in the scanning electron microscopy (SEM) image as shown in Fig. 4. Due to the lack of adhesion between the rubber particles and concrete, no continuous concrete particles or deformation traces caused by stripping are observed on the tire surface. The traces in the figure are due to the process of cutting applied while the tires are prepared for use in the concrete as aggregate. As can be clearly concluded from Table 7, porosity and capillary absorption values of the specimens increase with the increase of rubber content. The increase in porosity and capillary values suggests that the void of concrete increases in accordance with the rate of rubber particles. Therefore, this result is consistent with the data obtained through mechanical values.

3.2. Corrosion potential measurement results

The results obtained from the corrosion potential measurements of the steels embedded in the rubberized concrete specimens are shown in Fig. 5.

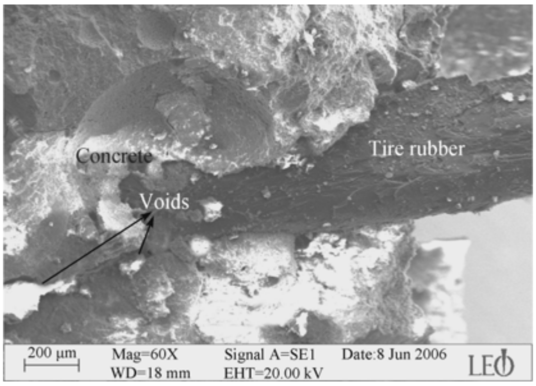

Fig. 4. SEM image of the rubberized concrete.

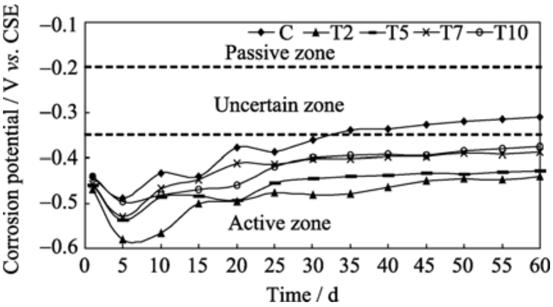

Fig. 5. Changes in corrosion potential of the specimens.

As seen in Fig. 5, the electronegative corrosion potential is much more in all the rubberized concrete specimens of any types compared to the control specimen. Furthermore, some decreases are observed in electronegative corrosion potential when the tire amount is increased. Indeed, the reinforcing steels in the control specimen become more passive compared to the specimens with tire addition and reach an uncertain zone in terms of corrosion at the end of the first month. The corrosion potentials of the steels in the specimens with tire addition remain in the active zone even at the end of 60 d. By taking ASTM C876 [11] as a reference, it is concluded that the corrosion still continues even at the end of 60 d in all the concretes with tire addition. From the results of corrosion potential by the ASTM C876 standard, the control specimen has a higher corrosion resistance than the rubberized concrete specimens.

The corrosion of steel in concrete is essentially an electrochemical process. Iron is oxidized to ferrous ions, which pass into the solution in the anode region. In the cathode region, oxygen is reduced to hydroxyl ions. The anode and cathode form a short-circuited corrosion cell with the flow of electrons in the steel and the flow of ions in the pore solution of the concrete [26]. In the anodic region, ferrous ions react with hydroxyl ions and generate ferrous hydroxide. Then, it is oxidized as ferric hydroxide. The following equations show these processes:

$$Fe^{2+}+2OH^{-}\rightarrow Fe(OH)_2 \tag{3}$$

$$4Fe(OH)_2+O_2+2H_2O\rightarrow 4Fe(OH)_3 \tag{4}$$

The deterioration effect of chloride ions during the electrochemical reaction is shown as

$$Fe^{2+}+2Cl^{-}+4H_2O\rightarrow FeCl_2\cdot 4H_2O \tag{5}$$

$$FeCl_2\cdot 4H_2O\rightarrow Fe(OH)_2\downarrow+2Cl^{-}+2H^{+}+2H_2O \tag{6}$$

From the equations, it can be seen that the chloride ion neither gets involved in the reaction nor is consumed by the reaction. However, the chloride ion plays an important role in transporting the corrosion product. It is the catalyst of corrosion reaction. NaCl added to the concrete mixture in order to create a corrosive atmosphere is the greatest factor in preventing the steels in the control specimen and the specimens with tire addition from becoming passive during the experiment process.

Corrosion potential measurements indicated that the tire addition decreased the corrosion resistance of reinforcing steels compared to the concrete without tire addition. This decrease in corrosion resistance resulted from the voids emerging due to the lack of adhesion between the concrete and tire particles. As known, the oxygen input into the concrete made the increase easy in void amounts of the concrete in porous structure. Oxygen and water are definitely required to enable corrosion to continue in a neutral environment [27]. Thus, the corrosion resistance of the steels in the rubberized concretes is also reduced since the oxygen input increases with the voids emerging with the tire addition.

As clearly seen in Fig. 5, a decrease is observed to some extent of the electronegative corrosion potential of reinforcing steels in the specimens with tire addition as a result of the increase in tire amount. This decrease in electronegative corrosion potential can be probably based on the fact that the tire addition may decrease the conductivity of the concrete because rubber is a non-conductive material. Benazzouk *et al.* mentioned that rubber waste particles, which replaced the cement, were a non-conductive material [28]. Therefore, the concrete with the least percentage of recycled rubber tire (2vol%) has a much more electronegative corrosion potential than the concrete with the rubber tire addition of 10vol%. In spite of this result, the voids resulting from the lack of adhesion between the concrete and tire particles reduced the corrosion resistance of the reinforcing steel in the rubberized concrete specimens of any types more compared to the control specimen.

3.3. Results of galvanic current measurements

The values obtained as a result of galvanic current measurements are shown in Fig. 6.

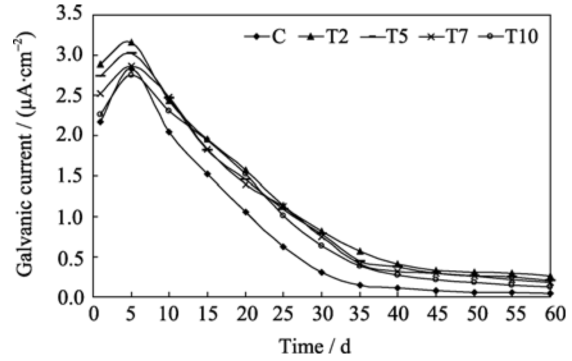

Fig. 6. Changes in galvanic current of the specimens.

Galvanic current measurement values seem to support corrosion potential values. High galvanic current values are found in all concrete blocks in just the following days of molding, but galvanic current values come close to zero after 45 d. It can also be understood from the galvanic current measurements that the tire addition leads to an increase in galvanic current of the concrete. This indicates that the corrosion rates of the steels embedded in the control specimen are relatively lower than those of the rubberized concrete specimens.

A decrease is observed, to some extent, to occur in the galvanic current values of reinforcing steels in the specimens with tire addition as a result of the increase in tire amount. The decrease in galvanic current depending on the increase in tire amount is displayed in Fig. 6. As can be concluded from Fig. 6, no significant difference is observed between the five sets of the results. Once again, the addition of 2vol% recycled tire appears to cause a more deleterious effect than the addition of 10vol%. As already specified, this is attributed to the fact that the conductivity of the concrete with more rubber particles (10vol%) may be lower than that of the concrete with fewer rubber particles (2vol%) because rubber is a non-conductive material. The values obtained from galvanic current measurements are in conformity with the corrosion potential values.

4. Conclusions

(1) The test results indicate that the unit weight of the concrete decreases as a result of the fact that certain ratios of vehicle tires are added to concrete instead of coarse aggregate. This is a desired situation. However, the increase in the amount of waste vehicle tires results in a decrease in compressive strength, tensile strength, and ultrasonic pulse velocity of the concrete, but an increase in porosity and sorptivity. This results from the lack of adhesion between the concrete and rubber particles.

(2) When waste vehicle tires are added to the concrete specimens instead of coarse aggregate, the corrosion rates of the steels embedded in these concretes increase more compared to the concrete specimens without tire addition.

(3) The corrosion rates of the embedded steels in the control specimen are relatively lower than those of the rubberized concrete specimens. In spite of this, an increase in vehicle tire content in the rubberized concrete causes a systematic decrease in corrosion rate of the embedded steels. In this study, the maximum rubber replacement is selected as 10vol%. It should be pointed out that further research should be carried out on the effects of higher rubber contents on the corrosion of steels.

(4) The use of waste vehicle tires in concrete instead of aggregate decreases the mechanical and physical strength of the concrete. This problem may be overcome by increasing the adhesion of tire particles with the concrete.

(5) This study helps resolve the problem of disposing waste vehicle tires, and some special characteristics of concrete can be achieved.

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