Introductory Behavior of Rubber Concrete

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ABSTRACT: This article introduces a new type of concrete, the so-called rubber concrete, and thereupon presents a way of modification of waste rubber to construction articles. The conventional cement concrete is made by mixing cement with sand and pebbles, but the rubber concrete proposed here virtually excludes cement completely. The manufacturing process of rubber concrete can be divided into two methods, which are designated for dry and wet processes, but this article focused just on the dry process. The physical properties of rubber composite increased with the silane treatment of added aggregates, but the volume of the aggregate might not be a critical factor affecting the compressive strength in the range of the aggregate contents used in this study, that is, the interfacial adhesion between the matrix rubber and the aggregates was a key factor to improve the mechanical properties of rubber concrete. The compressive strength of rubber concrete was about 89 MPa and the Poisson's ratio, which is the ratio of compressive-to-tensile strength, was 5.5%. From the viewpoint of the compressive strength and the Poisson's ratio, rubber concrete had better properties than those of conventional cement concrete. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 72: 35–40, 1999

Key words: waste rubber; scrap rubber; rubber concrete; compressive strength; Poisson's ratio

INTRODUCTION

Waste rubber has received a great deal of attention for disposal or utilization because of the large volume and difficulty of disposal. There are many ways for waste rubber to be useful.[1–4] However, to harmonize with our environment, waste rubber should be converted to a sophisticated form for better utilization.

Waste rubber can be disposed of by several methods. The easiest disposal method is just burial in a landfill. However, as waste rubbers discarded in a landfill tend to float on top, mosquito breeding or illegal disposal is causing severe environmental pollution. Rubber pyrolysis can be another method. Scrap tire pyrolysis has been the subject of several studies by rubber, oil, and carbon black industries. Also, scrap rubber as a fuel source is a possible method because incineration of scrap rubber has a high caloric value. Rubber asphalt appears to be a promising method in the future. The rubber improves asphalt ductility and increases the temperature at which the asphalt softens. Asphalt rubber is also used for a waterproofing membrane, a crack and joint sealer, a hot-mix binder, and roofing materials. As a consequence, the recycling of waste rubber must be the best choice for disposal of waste rubber.

As the world's needs for housing, transportation, and industry increase, the consumption of concrete products is expected to increase. Although portland cement concrete is one of the most remarkable and versatile construction materials, a clear need is perceived for the improve-

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ment of properties such as strength, toughness, ductility, and durability. One valid approach is to improve the concrete itself; another is to combine the well-known technology of a cement concrete formation with modern polymer technology. Generally, polymer concrete composites can be classified into polymer-impregnated concrete (PIC), polymer cement concrete (PCC), and polymer concrete (PC).[5] PIC is a precast and cured hydrated cement concrete which has been impregnated with a monomer, which is subsequently polymerized *in situ*. PCC is a premixture of cement paste and aggregate to which monomers were added prior to setting. PC is also an aggregate bounded with a polymer binder. According to the general definition, it is called concrete because concrete consists of any aggregate bound with a binder. Here, a new concept that is designated rubber concrete is proposed as one of the PC composites. This study, to optimize reuse of waste rubber, aimed to make rubber concrete by pulverizing waste rubber, followed by chemical treatment, mixing with aggregates, and molding of that mixture at high temperature and pressure. Rubber concrete comprises waste rubber as the matrix, which substitutes for cement in cement concrete. Consequently, the rubber matrix imparts both flexibility and hardness to concrete in order to compensate for the brittleness that is the main deficiency of cement concrete.

EXPERIMENTAL

Preparation of Matrix Rubber for Rubber Concrete

In this study, waste passenger tires were used as the source of waste rubber. The waste scrap rubber was supplied from the Jung Woo Chemical Co.(Kwangju, South Korea). The process to produce a waste scrap rubber was as follows: A waste tire was pulverized using a hammer mill at -60 to -80°C and it was further pulverized with a cracker mill. Large rubber particles were separated with a rotation-type separation screen and were returned to the cracker mill to reduce their size. The waste tires were pulverized eventually to the size of about 20–30 mesh through this process.

The matrix rubber, which would be the binder of rubber concrete, was prepared by two methods: The methods were designated as the dry and wet processes. In the case of the dry process, the scrap rubber was mixed with pine tar oil of 4 phr in a conventional mixer. Alternately, in the case of the wet process, the scrap rubber was dissolved in a solvent mixture based on 1,1,2,2-tetrachloroethane. Among many organic solvents, the preferred solvents having good dissolving power were the solvent mixture of 1,1,2,2-tetrachloroethane and methylene chloride with a volume ratio of 7 to 3, respectively. From an inspection of the solubility, it was known that the scrap rubber could be dissolved to the concentration of 50 g/dL at 120°C. This process was patented by the present authors.[6] The temperature of the mixture was increased with vigorous stirring so as to completely dissolve the scrap rubber in case of the wet process. The results obtained by the wet process will be presented later.

Effects of Aggregates on the Property of Matrix Rubber

The tensile test of matrix rubber containing various amounts of aggregates was performed to examine the effect of aggregates on the property of the rubber composite. The recipe consisted of 100 parts of pretreated scrap rubber with pine tar oil, 5 phr of sulfur, 8.8 phr of ZnO, 5.9 phr of stearic acid, and 5.9 phr of morpholinobenzothiazole. The compound was prepared by mixing rubber with curatives on a conventional mixer and the aggregates of 10, 20, and 30 phr were added to each compound. Here, the aggregates used were of two types: One was of coated aggregates with triethoxyvinylsilane and the other was of untreated aggregates. The aggregates were immersed in the triethoxyvinylsilane coupling agent for 2–3 h and then dried at about 40°C for 24 h. After mixing, the compounds were vulcanized in a compression-molding press at 160°C for 10 min. Tensile tests were performed on an Universal Testing Machine (UTM, Lloyd LR50K) according to ASTM D412. The strain rate and test temperature were 8.33 min^{-1} and 24°C, respectively.

Preparation of Rubber Concrete

Rubber concrete can be obtained by two processes, which are designated as the dry and wet processes. A schematic diagram of the manufacturing process for rubber concrete[6] is shown in Figure 1. However, this article deals with only the dry process. The aggregates passed through a #3 sieve were immersed in the triethoxyvinylsilane coupling agent for about 2–3 h and then dried at about 40°C for 24 h. Then, the aggregates were

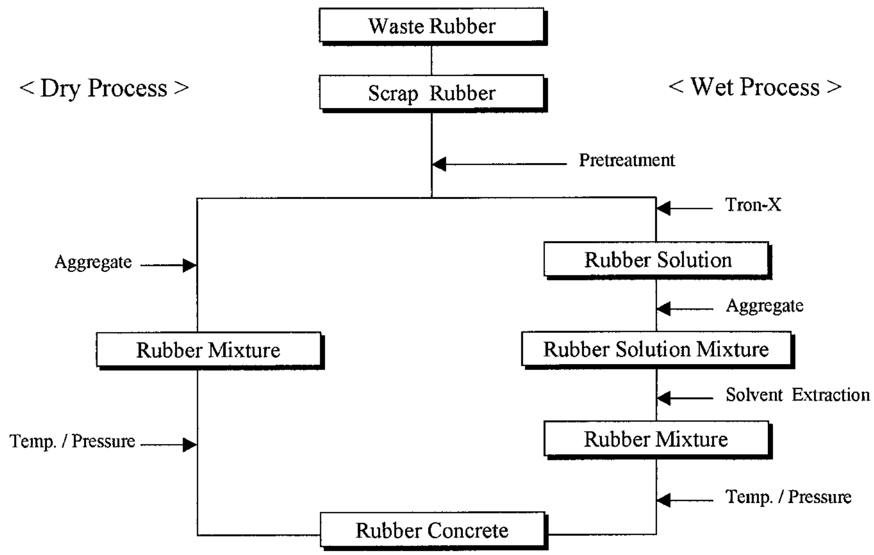


Figure 1 Manufacturing process of rubber concrete.

mixed with the compounded scrap rubber to prepare a rubber concrete composition. The mixtures were poured into a cylindrical casting having a diameter of 10 cm and a height of 20 cm and hardened using a vibrator for 10 min. Then, they were thermally treated under a pressure of about 20 MPa at 160°C for 1 h, thereby generating rubber concrete.

Mechanical Properties of Rubber Concrete

The test for compressive strength is so sensitive to variations in procedure that it must be carried out strictly according to a standard procedure. The compressive test was performed using a UTM (Zwick Model) according to ASTM C39. Because strength is dependent on the loading rate and test temperature, the specimen is then loaded at a deformation rate of 5 mm/min and 24°C until failure, which is defined as the maximum load the specimen can carry. The maximum load and type of failure are then reported.

Direct tension tests of concrete are seldom carried out, mainly because the specimen holding devices introduce secondary stresses that cannot be ignored. The most commonly used test for estimating the tensile strength of concrete is the ASTM C469 splitting tension test. The geometry of the tensile test is shown in Figure 2. In the splitting tension test, a specimen is subjected to compression load along two axial lines which are diametrically opposite. The load is applied continuously at a rate of 5 mm/min until the specimen fails. The compressive stress produces a transverse tensile stress that is uniform along the vertical diameter. The splitting tension strength considered as the tensile strength of rubber concrete is calculated by eq. (1)[5]:

$$T = 2P/\pi LD \tag{1}$$

where T is the tensile strength; P, the failure load; L, the length of the specimen; and D, the diameter of the specimen

RESULTS AND DISCUSSION

Effects of Aggregates on the Property of Matrix Rubber

Rubber concrete consists of waste rubber as the matrix and aggregates as the dispersed phase. Therefore, it is very important to examine how the aggregates affect the properties of the matrix rubber. The results are shown in Figure 3. In the

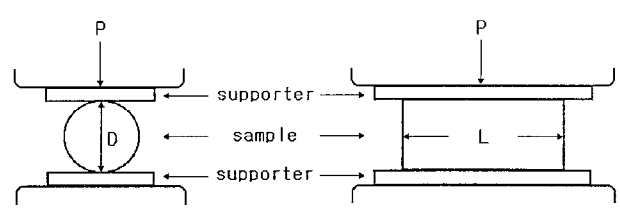


Figure 2 Geometry of tensile test for rubber concrete.

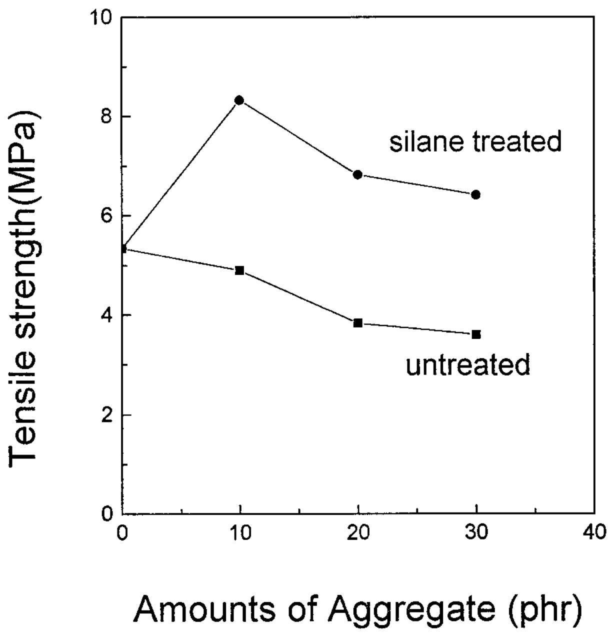


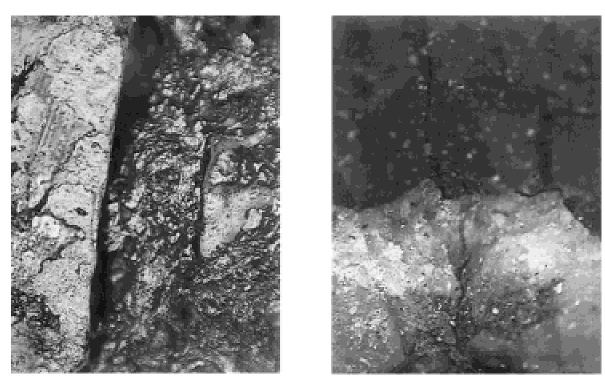
Figure 3 Tensile strength of matrix rubber with the amount of aggregates.

case of untreated aggregate, the tensile strength decreased with increase of the aggregate amounts as shown in Figure 3. It was thought that the adhesion between the matrix rubber and the aggregates was very poor. The more aggregates added, the more weak boundary layers would be produced at the interface between the matrix rubber and the aggregates. Thus, it resulted in a decrease of tensile strength. However, the tensile strength increased when the adhesion between the matrix rubber and the aggregates improved by the treatment of the aggregates with the triethoxyvinylsilane coupling agent. Figure 4 shows photographs of the fractured surface obtained by an image-analysis technique using a polarized optical microscope (Nikon OPTIPHOT2-POL). The results supported the above idea. In the case of Figure 4(a), using untreated aggregates, the failure proceeded at the interface between the matrix rubber and the aggregate, but the fracture occurred within the aggregate instead of at the interface with increasing interfacial adhesion [Fig. 4(b)]. The tensile strength passed through the maximum at 10 phr of the silane-treated aggregate. It was not certain why the tensile strength was maximum at 10 phr of the aggregate. However, it was thought that weak boundary layers might be produced with increasing aggregates due to an inhomogeneous silane coating of the aggregates. Up to now, it was found that the mechanical properties of a rubber composite could be improved with the addition of aggregates provided that the adhesion between the matrix rubber and the aggregate was strong enough.

Mechanical Properties of Rubber Concrete

In the design and quality control of concrete, strength is the property generally specified. This is because, compared to most other properties, testing of the strength is relatively easy. Furthermore, many properties of concrete, such as the elastic modulus, watertightness, or impermeability and resistance to weathering agents including aggressive waters, are directly related to strength and can therefore be deduced from the strength data.

The compressive strength of concrete is many times greater than other types of strength, and a majority of concrete elements are designed to take advantage of the higher compressive strength of the material. Although, in practice, most concrete is subjected simultaneously to a combination of compressive, shearing, and tensile stresses in two or more directions, the uniaxial compressive test is the easiest to perform in the laboratory. Also, the compressive test is accepted universally as a general index of concrete strength. The compressive strength of rubber concrete with a weight ratio of rubber to aggregate was examined. Because the most important parameters of the aggregate are the shape, texture, and size, the parameters thus were controlled herein. Also, the aggregates used were coated with the triethoxyvinylsilane. The results are listed in Table I.



(a) (b)

Figure 4 Photographs of fractured rubber composite (×100): (a) untreated aggregates; (b) treated aggregates.

Table I Compressive Strength of Rubber Concrete with the Weight Ratio of Rubber to Aggregate

	Rubber/Aggregate			
Properties	0.2/1	0.6/1	1/1	1.4/1
Compressive strength (MPa)	82.1	89.3	86.3	83.8
Compressive strain (%)	4.3	3.3	6.2	10.6
Density (g/cm^3)	2.06	1.96	1.84	1.78

As shown in Table I, the compressive strength passed through the maximum at a 0.6/1 rubber/aggregate weight ratio. However, the amounts of aggregates might not be a critical factor affecting the compressive strength in the range of aggregate contents used in this study. In general, the compressive strength of about 20 MPa corresponds to the general strength of cement concrete. As the compressive strength increases to 40 or more than 80 MPa, that range of strength indicates high or ultrahigh strength concrete. Then, the rubber concrete manufactured here corresponded to ultrahigh strength concrete in the viewpoint of compressive strength. Also, the rubber concrete was lightweight concrete compared with the conventional cement concrete as its density ranged from 1.78 to 2.06 g/cm^3 depending on the amount of the aggregates.

With a material such as concrete, which contains void spaces of various sizes and shapes in the matrix and microcracks at the transition zone between the matrix and coarse aggregates, the failure modes under stress are very complex and vary with the type of stress. In compression, the failure mode is less brittle because considerably more energy is needed to form and to extend cracks in the matrix, while, in uniaxial tension, relatively less energy is needed for the initiation and growth of crack in the matrix. As the uniaxial tension state of stress tends to arrest cracks much less frequently than does the compressive state of stress, the interval of stable crack propagation is expected to be short. The tensile test of rubber concrete with the 0.6/1 rubber/aggregate ratio was performed according to ASTM C496. The results are listed in Table II and compared with the conventional cement concrete and polymer concrete. As shown in Table II, the tensile strength of rubber concrete fell under the upper range of that of the conventional cement concrete, but in a lower range of that of polymer concrete.

For a material subjected to simple axial load, the ratio of the lateral axial strain to axial strain within the elastic range is called Poisson's ratio, that is, the ratio between the uniaxial tensile and compressive strength is known as the Poisson's ratio. The compressive and tensile strength are closely related. However, there is no direct proportionality. As the compressive strength of concrete increases, the tensile strength also increases but at a decreasing rate. In other words, the tensile/compressive strength ratio depends on the general level of the compressive strength, that is, the higher the compressive strength, the lower the ratio, generally above 10% for low-strength, 8–9% for medium-strength, and 7% for high-strength concrete. Owing to the fact that cracks can propagate under a tensile stress with ease, this is not surprising. Therefore, most concrete elements are designed under the assumption that the concrete would resist the compressive stress but not the tensile stress. However, tensile stress cannot be ignored at all because cracking of concrete is frequently the outcome of a tensile failure caused by restrained shrinkage. The calculated Poisson's ratio of rubber concrete was 5.5% based on Tables I and II, which corresponded to the value of ultrahigh strength concrete.

Fracture Mode of Rubber Concrete

It is generally agreed that in a uniaxial compression test on medium- or low-strength concrete no cracks are initiated in the matrix up to about 50% of the failure stress.[7] At this stage, a stable system of cracks, called shear-bone cracks, already exists in the vicinity of coarse aggregates. At a higher stress level, cracks are initiated within the matrix and their number and size increase progressively with an increasing stress level. The cracks in the matrix and the transition zone eventually join up, and, generally, a failure surface

Table II Comparison of Tensile Strength with Types of Concrete

Types of Concrete	Tensile Strength (MPa)
Portland cement concrete[a]	1–5
Epoxy polymer concrete[a]	9–10
Rubber concrete	4.91

[a] The data were quoted from ref. 5.

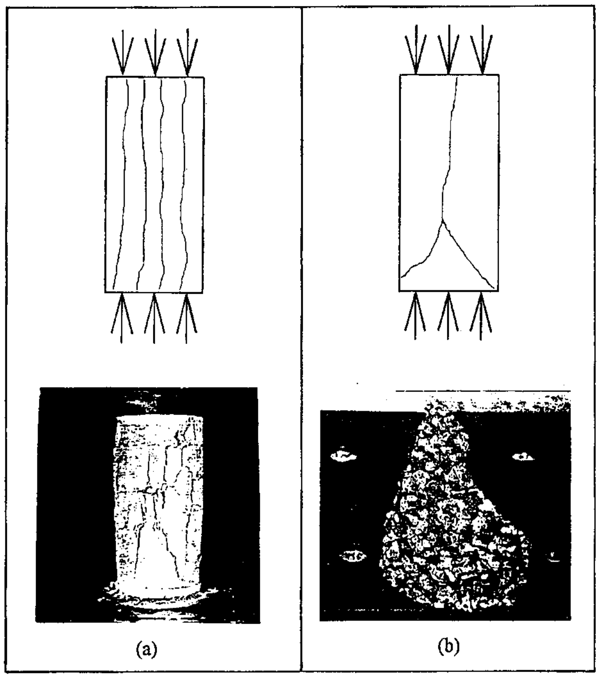


Figure 5 Conventional cement concrete and rubber concrete fractured by compressive load: (a) cement concrete; (b) rubber concrete.

develops at about 20–30° from the direction of the load. Since compression tends to squeeze molecules closer together, it is hard to see how pure compression can lead to failure. In a compression test, however, there is also secondary tensile stress induced in the specimen, at a right angle to the axis of the specimen. Since concrete is relatively weak in tension, this stress may cause cracking and failure. For ordinary concrete, with a Poisson's ratio approximately equal to 20%, such a lateral tensile strain will occur at fairly low compressive loads, and this could be the cause of failure along the direction of the load. This is probably the natural mode of failure in pure compression. The induced shearing stress due to an end restraint may cause an apparent shear failure of the specimen and it is likely that failure occurs through some combination of shear and tensile forces. The schematic and real pictures of fractured conventional cement concrete and rubber concrete under a compressive load are shown in Figure 5. As shown in Figure 5(a), the failure occurred along the direction of the load and resulted in low compressive strength. However, the rubber concrete left the bell-shaped fragment after fracture and resulted in a high compressive strength [Fig. 5(b)]. Also, the results agree well with the mechanism described previously, which is the fracture result caused by the combination of shear and tensile forces.

CONCLUSIONS

This article focused on the principal properties of rubber concrete made by the dry process. The following conclusions were derived from the study:

1. The aggregates acted as a filler on the matrix rubber if the interfacial adhesion between the matrix rubber and the aggregates were strong. However, the amount of the aggregates were not a critical factor affecting the mechanical property of rubber concrete.
2. The density and compressive strength of rubber concrete ranged from 1.78 to 2.06 g/cm^3 and 82.1 to 89.3 MPa with the aggregate amount, respectively. This means that the rubber concrete must be lightweight and ultrahigh strength concrete compared with the conventional cement concrete.
3. The Poisson's ratio of the rubber concrete was 5.5%, which corresponded to the value of ultrahigh strength concrete.
4. The failure surface developed with some degrees from the direction of the load and the fracture behavior was agreed well with the theory suggested for cement concrete.

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