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Study of the Evolution of Properties of Concrete Containing Used Tire Aggregates

Mamery Adama Serifou[1], Ouaga Jean Bruce Nataniel Gboga[2], Bleh Raoul Ulrich Kouassi[3]*, Edjikémé Emeruwa[1]

[1]Laboratoire des Sciences du Sol, de l'Eau et de Géomatériaux, UFR des Sciences de la Terre et des Ressources Minières, Université Félix Houphouët Boigny, Abidjan, Côte d'Ivoire
[2]Institut National Polytechnique Félix Houphouët-Boigny, Yamoussoukro, Côte d'Ivoire
[3]Laboratoire de Géomatériaux et de Géotechnique, Département des Sciences de la Terre, UFR Environnement, Université Jean Lorougnon Guédé, Daloa, Côte d'Ivoire
Email: smadamsdedjen@yahoo.fr, gboga.jb65@gmail.com, *kbraoul@ujlg.edu.ci, ediksmat@yahoo.com

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Abstract

Concrete is generally composed of cement, water, gravel, and sand. However, some research focuses on substituting aggregates with waste materials. In this study, used tires are used as a substitute for gravel. Characteristics such as tensile strength, compressive strength, and porosity were monitored at 7, 14, and 28 days of maturation. The results show that aggregates made from used tires are suitable for concrete production and can replace natural gravel. Regarding the formed concrete, low substitution rates lead to improved concrete properties, but only at an early age. A reaction between the cement and rubber could be the underlying cause. Additionally, the products of this reaction may mitigate the evolution of the compressive strength of the concrete over time.

Keywords

Concrete, Used Tire, Porosity, Mechanical Strength

1. Introduction

Concrete is the most widely used construction material in the world, both in building and public works [1]. There are different types of concrete, including reinforced concrete, fiber-reinforced concrete, prestressed concrete, shotcrete, and ready-mix concrete [2]. To address issues related to the scarcity of natural aggregates, the use of other types of aggregates is being considered. In this context, waste materials such as rubber waste have been used in concrete. The use of used tires in concrete reduces its deformation and prevents crack development [3].

Other benefits include improved thermal insulation, building energy balance, and durability against physico-chemical attacks [4]. However, most studies have revealed drawbacks such as decreased mechanical properties and increased porosity [5] [6]. Are there conditions under which the integration of used tires in concrete would be beneficial for these parameters? This study, titled "Study of the Evolution of Properties of Concrete Containing Used Tire Aggregates," was conducted to answer this question. To achieve this objective, the influence of the substitution rate of natural aggregates with used tires on tensile strength, compressive strength, and porosity was first studied. Then, the evolution of these parameters over time was observed.

2. Materials and Methods

2.1. Raw Materials

2.1.1. Natural Aggregates

Two types of natural aggregates were used: sand and gravel. The sand was collected from the Ebrié Lagoon in the locality of Abidjan, while the gravel came from a granite crushing quarry in the locality of Azaguié (in the south of Côte d'Ivoire).

2.1.2. Recycled Aggregates: Used Tires

The tires used are worn and discarded tires found in the streets. They were collected in Abidjan, specifically in the Cocody district. After collection, the material was cut into particles ranging in size from five to fifteen millimeters (**Figure 1**).

Figure 1. Tire aggregates.

2.1.3. Cement and Water

The cement used is a locally manufactured standard Portland cement of the Bélier brand. It belongs to the CPJ-CEM II family of cements and has a nominal strength of 42.5 megapascals. As for the mixing water, it is potable water from the local distribution network.

2.2. Methodology

2.2.1. Sieve Granulometric Analysis (NF EN ISO 17892-4)

A 1500-gram sample of aggregate is used for this test. After washing and drying, the samples are placed on top of a sieve column and shaken for half an hour. The residues on each sieve are weighed, resulting in granulometric curves. These curves are used to determine the granular class, the Hazen uniformity coefficient (Cu), the curvature coefficient (Cc), and the Fineness Modulus (Mf) exclusively for the sand.

2.2.2. Specific Weight (NF EN ISO 17892-3)

The test involves introducing a 250-gram mass of aggregate into the pycnometer. Then, it is filled with distilled water while ensuring there is no air in the mixture. The whole setup is weighed, and a dedicated abacus for the test is used to obtain the specific weight of the aggregate.

2.2.3. Composition and Sample Preparation

The different dosages used to prepare the concrete samples are recorded in Table 1. In each of them, the quantities of cement and sand are constant and respectively equal to 400 kg and 644.1 kg. Depending on the formulation of the control concrete (BT), the other concretes were formulated by substituting 5% (BR5), 10% (BR10) and 15% (BR15) of natural gravels with used tire aggregates.

Table 1. Concrete composition.

	Natural Gravel (kg)	Recycled Tire Gravel (kg)	Water (L)
control concrete (BT)	1026.9	0	217.8
BR5%	975.6	51.3	217.8
BR10%	924.2	102.7	217.8
BR15%	872.9	154	217.8

All the concretes were cast in prismatic molds with dimensions of 7 × 7 × 28 cubic centimeters. The specimens were de-molded the day after casting and kept in a water basin. Physical and mechanical tests were conducted at 7, 14, and 28 days of maturity.

2.2.4. Three-Point Bending Test (NF P18-407)

The flexural tensile strength is obtained using a hydraulic press. The samples are placed on two supports, and a gradually increasing force is applied at their midpoint by an upper plate until failure (Figure 2).

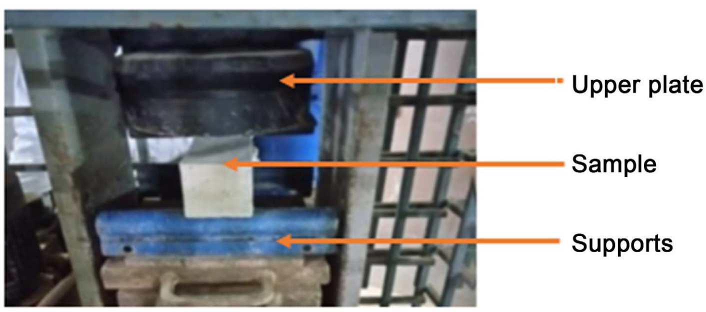

Figure 2. Three-point bending test setup.

This strength is determined by the following relationship:

$$A = \frac{3 \times F \times L}{2 \times l \times e^2} \quad (1)$$

with: *A*: flexural strength (MPa), *l*: thickness (mm), *L*: length of the prism (mm), *e*: height (mm), *F*: Force recorded at rupture (N).

2.2.5. Compressive Strength Test (NF P18-406)

The equipment used is also a hydraulic press. The test is conducted on half of the prismatic specimens from the tensile test. In the latter, the maximum load supported is measured, and then the compression strength is determined using the formula:

$$R_c = \frac{F}{S} \quad (2)$$

with: R_c: compression strength (MPa), *F*: applied compressive force (N), and *S*: surface area of the concrete cylinder (m^3).

2.2.6. Hydrostatic Weighing

Hydrostatic weighing was used to determine the porosity of the samples. The equipment used is shown in **Figure 3**. For this procedure, pieces of specimens were taken after the mechanical tests. They were dried in an oven at 105˚C for 24 hours and weighed to obtain the dry mass (Ms). They were then immersed in water for 24 hours. Weighing the sample in the water-filled reservoir of the hydrostatic balance provided the submerged mass (Me). Finally, the samples were gently dried with a dry cloth to remove any surface water and weighed on the balance platform to obtain the air mass (Ma).

Figure 3. Hydrostatic balance.

These different masses obtained allow calculating the porosity and density of the samples according to the following relationships:

$$\eta = \frac{\text{MA} - \text{MS}}{\text{MA} - \text{ME}} \times 100 \quad (3)$$

with η: porosity of the specimen (%).

3. Result

3.1. Properties of Aggregates

3.1.1. Particle Size Analysis

The particle size distribution curves of the aggregates are shown in Figure 4, and their interpretations are recorded in Table 2 and Table 3.

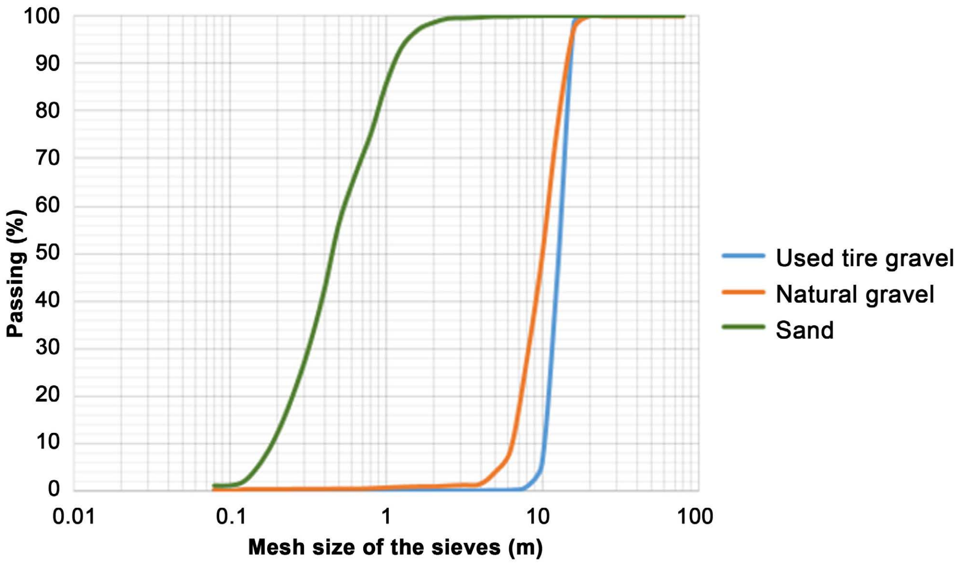

Figure 4. Particle size distribution curves.

Table 2. Physical properties of aggregates.

Properties	Mf (%)	Cu (%)	Cc (%)	d/D (mm)	P.S (g/cm³)
Sand	2.12	2.81	0.98	0/1	2.67
Naturel gravel	-	1.73	0.79	6/15	2.65
Tire gravel	-	1.36	1.02	10/15	1.16

The sand is of grain size class 0/1 with a fineness modulus of 2.12, categorizing it as fine sand within the particle size distribution. Using this type of sand in concrete production results in good workability and low strength. Additionally, the coefficient of uniformity (Cu) is 2.81 and the coefficient of curvature (Cc) is 1.01. These values classify the sand as well-graded and broadly graded, indicating that its use leads to a denser concrete due to a compact arrangement of particles.

As for the natural aggregates and those from tires, they are respectively of grain size class 6/15 and 10/15, which are relatively close classes. This similarity is also reflected in their coefficient of uniformity and coefficient of curvature. Therefore, substituting one for the other would not significantly alter the particle size distribution. Moreover, Cu values below 2 and Cc values below 1 categorize these aggregates as poorly graded materials with a tight particle size distribution. This, combined with the well-graded sand, contributes to achieving good material compactness.

3.1.2. Specific Weights

The specific weights of the aggregates are recorded in Table 3 below:

Table 3. Specific weights

	Sand	Natural gravel	Tire gravel
Specific weights (g/cm³)	2.67	2.65	1.16

The specific gravity of sand and natural aggregates is 2.67 grams per cubic centimeter and grams per cubic centimeter, respectively. These values correspond to the typical densities of aggregates commonly used in concrete production, making them suitable for the formulation of the control concrete. As for tire aggregates, their density of 1.16 indicates their potential use as aggregates in concrete.

3.2. Mechanical Properties of Concrete

3.2.1. Tensile Strength by Flexural Bending

Figure 5 shows the results of the three-point flexural tensile strength of the various concrete mixes prepared.

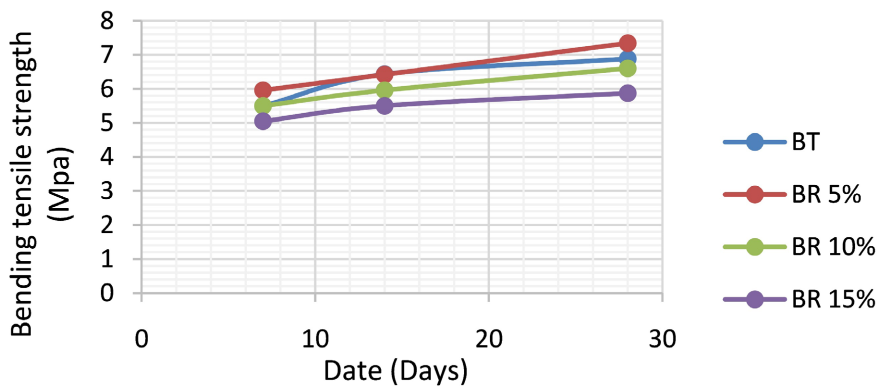

Figure 5. Tensile strength by flexural bending.

The tensile strengths in three-point flexural bending increase over time due to the cement hydration reaction that optimizes the mechanical properties of cementitious materials. Additionally, the substitution rate of natural aggregates with tires influences these strengths. BR5% shows higher tensile strength compared to the control concrete. However, increasing the tire proportion beyond 10% leads to a significant decrease in this property. Therefore, this study concludes that at low substitution rates, tire aggregates enhance the tensile strength of concrete.

3.2.2. Compressive Strength

Figure 6 shows the results of the compressive strength of concrete specimens.

Initially, it appears from this figure that at an early age (7 days), the compressive strength of BR5% is higher than that of all other mixes. This result could be attributed to the fact that the used tire helps improve concrete strength by reducing its porosity. However, at higher substitution rates, the decrease in compressive strength can be attributed to the characteristics of the used tire itself. Furthermore, the compressive strength of all mixes increases over time. It increases by 76% for the control concrete (BT) from the seventh to the twenty-eighth day, while the average growth rate for samples containing used tire aggregates is around 8%. The increase in strength is linked to the production of cement hydrates, suggesting that the hydration reaction of cement may be inhibited by the presence of used tire aggregates. However, the strength decreases with increasing substitution rates.

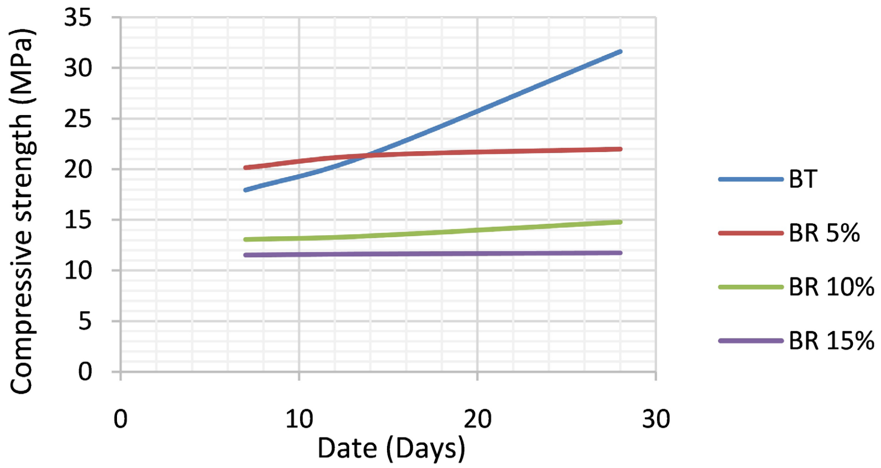

Figure 6. Compressive strength.

3.3. Porosity

The variation in porosities of the different samples is presented in Figure 7 below.

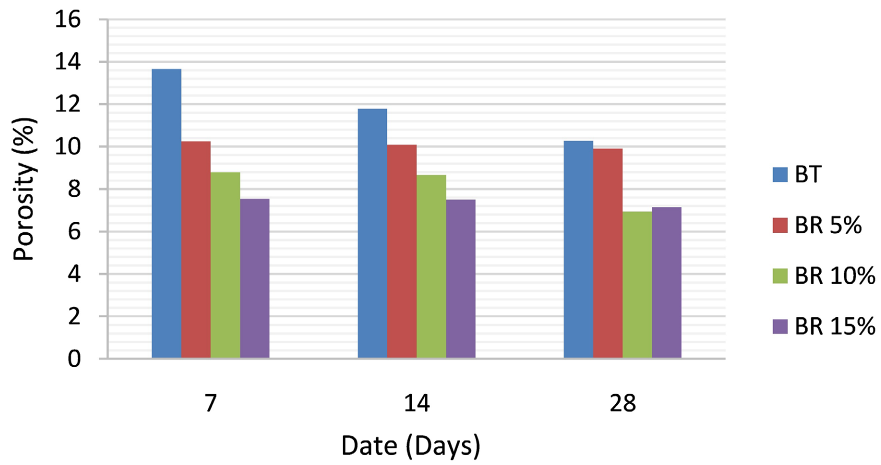

Figure 7. Concrete porosity.

In the presence of used tires, the porosity of the concrete is low. Given the similar particle sizes of both types of aggregates, one could consider an early reaction between the rubber in the used tires and the cement (with the other components being inert). The products of this suspected reaction might contribute to sealing the pores in the materials, similar to how cement hydrates work. However, this reduction in porosity does not translate into improved compressive strength, as shown in **Figure 6**. The pore-sealing elements in the concrete may not effectively enhance compressive strength. It's also worth noting that porosity decreases over time and with increasing tire content. However, at 5% tire content, porosity varies very little with age of maturation.

4. Discussion

All aggregates used are suitable for concrete production. Fine sand is commonly used in concrete manufacturing, contributing to its good workability and low strength [7], a claim also supported by [8]. These sands, rich in fines, represent an attractive alternative from a technical, economic, and ecological perspective for concrete formulation. The two types of aggregates used, natural and from tires, can be substituted for each other due to their similar granular characteristics. They are classified among "small aggregates" with a maximum dimension "D" less than or equal to 16 mm [9].

Moreover, studies on the substitution of natural aggregates with rubber aggregates, such as those conducted by [10], show grain size distributions similar to inert skeleton. Natural aggregates, with a specific weight greater than 2 g/cm^3, are commonly used in concrete [11]. As for tire aggregates, their specific mass is similar to that obtained by [1] in his work on recycled material-based concretes.

The concretes resulting from the use of these aggregates are usable in civil engineering. According to [12], cementitious materials with porosity greater than 16% have very low durability (<30 years). However, concretes based on used tires have a porosity ranging from 7.14% to 9.91% after 28 days of maturation, making them durable. Furthermore, Eurocode 2 recommends a minimum flexural strength of 4.1 MPa for concretes used in construction. The characterized samples show flexural strengths between 5.87 MPa and 7.34 MPa. In contrast, compressive strengths vary between 11.73 MPa and 22 MPa, whereas the recommended value is 25 MPa, indicating a need for improvement. However, standard NF EN 206/CN classifies these concretes in the LC 20/25 category, suitable for lightweight foundations such as strip or isolated footings, as well as ground slabs on void.

This study has highlighted optimal properties of concretes containing used tire aggregates at an early age, contrary to performances observed after twenty-eight days. [13] observed that the mechanical strengths of concretes with tire aggregates were lower than those of controls. This decrease is attributed to the low density of tire aggregates compared to mineral aggregates, as well as limited adhesion between cement paste and rubber particles. [4] also observed adhesion problems between tire aggregates and the cement matrix through scanning electron microscope analyses. The addition of rubber particles leads to significant additional porosity at the Tire Aggregates/Binder interface. To address these issues, chemical treatments with S_2HO_4 and mechanical treatments with sand-glue and unground slag-glue have been applied to tire aggregates, improving the roughness of the interface. According to [14], the decrease in mechanical properties after twenty-eight days can be explained by the flexibility of rubber compared to natural aggregates. [10] specify that incorporating rubber aggregates into concrete should not pose a problem if the substitution rate remains below 5% by mass, thereby explaining the observed improvement in properties with this substitution rate. [15] also observed a decrease in water-accessible porosity with increasing rubber content, attributed to the hydrophobic nature of the material. Furthermore, the compressive strength of all samples increases with time, as observed by [16], due to the production of cement hydrates in the environment. However, the reduction of this growth in the presence of used tire aggregates suggests the formation of an inhibitory product, likely linked to a chemical reaction of the tires.

Thus, this study has revealed the possibility of improving the compressive strengths of concrete by substituting up to 5% by mass of natural aggregates with tire aggregates, primarily at a young age.

5. Conclusion

Sustainable development mandates the valorization of all forms of waste. Used tires can be incorporated into cementitious materials, but they are known to bring drawbacks on mechanical properties as concrete reaches maturity. This study aimed to track the evolution of compressive and tensile strength, as well as porosity, of concrete where natural aggregates were partially substituted with tire aggregates. Tests were conducted at 7, 14, and 28 days. The results highlighted that tire aggregates can enhance the mechanical strengths of concrete at a young age and with a substitution rate of 5%. This reveals an early chemical reaction between rubber and cement, which could explain the observed improvements. The product of this reaction mitigates the evolution of concrete strength. Subsequent studies could focus on controlling the parameters of this reaction and its products.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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