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Mechanical and optical micrographic analysis of rubberized concrete for pavement infrastructure reinforcement

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Abstract – In this research the mechanical performance of developed composites, namely the crumb rubber concrete (CRC) and ground tire rubber concrete (GTRC) was assessed to verify their suitability regarding the strengths specified by various technical guidelines used in rigid pavement structural design. Despite feasibility tests reported in the literature, the incorporation of rubber adversely affects the mechanical characteristics of the resulting composites. The focus lies in evaluating compressive and tensile strengths, as well as flexural and splitting strength of rubberized concrete. Traditionally, compressive strength serves as the reference characteristic for cementitious materials. However, in the case of rigid pavements, they function as multilayer structures primarily subjected to tensile forces due to repeated heavy loads. Consequently, concrete experiences premature cracking due to its limited deformation capacity. Visual and optical micrograph analysis of various composites under compression and tension reveals their structural integrity and remarkable ability to restrict crack propagation within the cementitious matrix. The interlocking of crack lips, typically oriented parallel to applied loads, and the behavior of rubberized composites after fracture prompt reflection on the dissipative and energy-absorbing effects of elastomers. Notably, fine ground tire rubber used in GTRC exhibits a favorable tendency to withstand transferred stresses. This research provides valuable insights into the mechanical behavior of rubberized concrete, emphasizing its potential for durable and resilient applications.

Keywords – Rubberied Concrete; Mechanical Performance; Optical Micrograph Analysis ;Crack Propagation; Energy Absorption

I. INTRODUCTION

It is known that the predominant impact of incorporating rubbers into cementitious materials results in a reduction of certain mechanical properties of the composite [1]-[7]. However, this behavior must largely be accepted due to the low rigidity of rubber aggregates [8],[9]. On the other hand, improving the bonds between rubber and cementitious matrix leads to enhanced durability properties as well as mechanical properties of the composites. Indeed, several authors have proposed solutions to strengthen the weak bond between these elastomers and the cementitious matrix, such as using a chemical treatment based on "NaOH" solution to modify the adhesion properties of rubber particles [10]. Similarly, other solutions have been suggested to potentially enhance the mechanical strengths of rubberized concretes by incorporating additives into the composites such as silica fume [11]. In another study, investigated by Mohammadi et al. [12], a method of introducing rubber particles into mixes through a wet process called "water-soaking" demonstrates an improvement in the mechanical properties of concretes with a uniform distribution of rubber particles in the cementitious matrix.

However, these methods may be uneconomical and costly when undertaking large-scale projects or designing structures with large surface areas such as industrial floorings or rigid pavements. It is in this context that in this work the use of rubber particles in all concrete mixes was established without any particular treatment of the elastomers, thus allowing for real gains both economically and environmentally. However, several studies present other interesting properties obtained for rubberized composites and ideally usable for pavements, such as better deformation capacity, improvement in behavior resulting in high post-peak residual strengths [13],[14], but also and above all, low sensitivity to cracking [15]. Thus, the roles of rubbers in cementitious materials are revealed to be crucial from the perspective of effectively minimizing the brittleness of cement concrete intended for rigid pavement design.

II. MATERIALS AND METHOD

A. *Materials*

In this study, conventional methods of cement concrete formulation for pavement design are applicable in the case of composite concretes. The Dreux-Gorisse method [16] was chosen to allow the use of a smaller quantity of cement and a larger quantity of aggregates, translating into better mechanical characteristics of rubberized concretes. To make a good comparison with conventional concrete, and to avoid the negative effect of excessive water affecting the mechanical properties, the water/cement ratio (w/c) is kept constant and equal to 0.45. To evaluate the effect of the addition of rubberized wastes on the performance of cement concrete, two types of mixes were prepared and compared: a Crumb Rubber Concrete (CRC) and Ground Tire Rubber Concrete (GTRC) with five rates of partial volume substitution of sand at different rubber contents: 0, 10, 15, 20 and 25%. The details of this formulation are presented in a previously published study [9].

The dry materials were mixed in a motorized planetary mixer, then water and a superplasticizer (SP) additive were added in fixed doses and mixed for three minutes until a fresh and homogeneous mixture was obtained. The air-entraining agent (AEA) was added to this mixture for a further two minutes. After that, the molds were filled in three layers and placed on a vibrating table for good compaction (One minute for each layer). All specimens were then removed from the molds after 24 hours of fabrication and stored in a concretes conservation room for 28 days under standard curing conditions at 20 ± 2 °C and between 60% and 80% relative humidity.

B. *Method*

The compressive and splitting tensile strengths of both conventional concrete and various rubberized composites were determined on cylindrical specimens with a diameter of 110 mm and a height of 220 mm. It is worth noting that all samples were stored in a concrete curing room at 20 ± 2°C and between 60% and 80% relative humidity for a curing period of 28 days. Subsequently, to ensure uniform loading during the compression test, the upper faces of the cylindrical specimens were ground using a concrete surface grinder as depicted in Fig. 1. The hydraulic press used for this test was a PERRIER-type automatic control press with a capacity of 3000 kN, as shown in Fig. 1. Compressive strength was evaluated according to standard EN 12390-3 under force control and at a loading rate of 0.5 MPa/s. At failure, the maximum load was displayed on the press dial, and the compressive strength was calculated using the expression presented below, with an average of three measurements taken for each composition.

$$f_{c28} = \frac{F_c}{A_c} \tag{1}$$

Where:

f_{c28} represents the compressive strength expressed in MPa (megapascals);

F_c represents the maximum load expressed in N (newtons);

A_c represents the cross-sectional area of the cylindrical specimen in mm² (square millimeters).

The test for measuring the splitting tensile strength was conducted in accordance with standard EN 12390-6 under force control and at a loading rate of 0.05 MPa/s. At failure, the maximum load was displayed using the data acquisition system of a Shimadzu electromechanical press with a nominal capacity of 250 kN, as shown in Fig. 1. The splitting tensile strength was calculated according to the expression presented below, with an average of three measurements taken for each composition.

$$f_{ct} = \frac{2 \times F_t}{\pi \times L \times d} \tag{2}$$

Where:

f_{ct28} represents the splitting tensile strength expressed in MPa (megapascals);

F_t represents the maximum load expressed in N (newtons);

L represents the length of contact of the line on the cylindrical specimen in mm (millimeters);

d represents the nominal diameter of the specimen in mm (millimeters).

For the measurement of flexural tensile strength, prismatic specimens with dimensions of 70×70×280 mm were prepared following a three-point bending scheme according to the European standard EN 12390-5, using a Shimadzu electromechanical press with a maximum load capacity of 250 kN imposing a constant loading speed under displacement control of the crosshead set equal to 0.1 mm/min. The experimental setup, as well as the sample arrangement procedure, is presented in Fig. 1. At failure, the maximum load was displayed via the press acquisition system, and the flexural tensile strength was calculated according to the expression presented below, with an average of three measurements taken for each composition.

Where:

$$f_{cf} = \frac{3}{2}\frac{F_p l}{d_1 d_2^2} \tag{3}$$

f_{cf} represents the three-point flexural tensile strength expressed in MPa (megapascals);

F_p represents the maximum load expressed in N (newtons);

l represents the span length between the two support rollers in mm (millimeters);

d_1 and d_2 represent the dimensions of the cross-sectional area of the specimen expressed in mm (millimeters).

Fig. 1 Experimental setup used for measuring the mechanical performance of concrete

III. RESULTS

The evolution of compressive strengths of the different composites at 28 days, as well as all experimental results, are provided in Table 1. As expected, compressive strengths are higher in the case of composites with smaller rubber particles. They decrease significantly with the increase in rubber volume content but remain within compatible values for use in wearing courses or foundation layers in a rigid pavement structure according to standard NF P 98-170 and standard EN 13870-1, with contents of 15% for composites with rubber aggregates and 25% for composites with rubber powder. Thus, this evolution is slightly influenced by the type and size of the elastomers. Figure 2, which compares the rate of compressive strength loss for all volume contents based on the particle size distribution of the rubber inclusions, shows that the higher the rubber size, the greater the decrease in mechanical strength compared to conventional concrete.

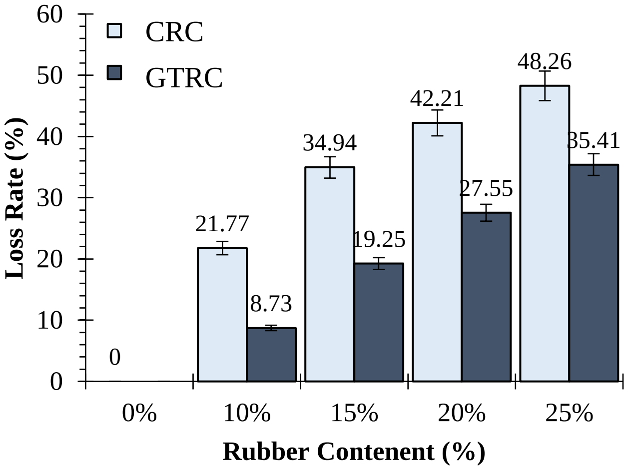

Fig. 2 Evolution of the loss rate in compressive strength compared to conventional concrete for CRC and GTRC composites

The 28-day results of split tensile strength tests for composites containing different rubber volumes are presented in Table 1. Similar to the compressive strength results, this figure illustrates the detrimental effect of rubber particles on the split tensile strength of conventional concrete as well as different rubberized composites depending on the rubber incorporation rate. However, it can be observed that for all volumes of rubber powder incorporation, the split tensile strength of GTRC composites exceeds 1.7 MPa, the minimum value required for usability in the design of rigid pavements (wearing course or foundation layer), according to the specifications of standards NF P 98-170 and EN 13877-2. Conversely, for rubber aggregate incorporation volumes of 20% and 25%, the split tensile strength of CRC composites shows values below 1.7 MPa but above 1.3 MPa, making them unsuitable for use in a wearing course in rigid pavements due to their low mechanical properties, yet still usable in a foundation layer.

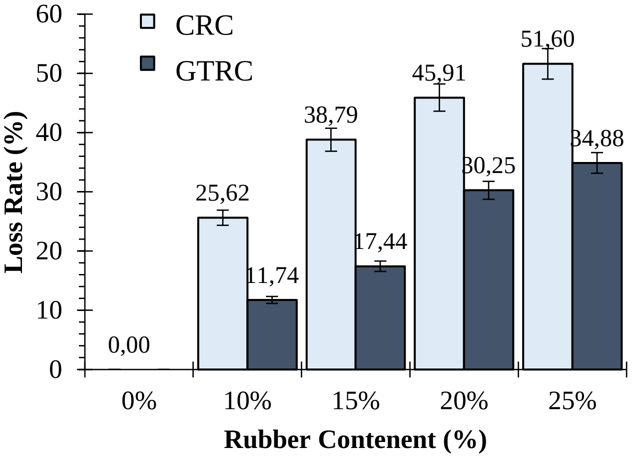

Fig. 3 Evolution of the loss rate in split tensile strength compared to conventional concrete for CRC and GTRC composites

However, it can be observed in Fig. 3 that the reduction is always less significant in the case of composites with smaller rubber particles due to the greater compactness of GTRC specimens compared to CRC specimens.

The 28-day results of flexural tensile strength tests for composites containing different rubber volumes are presented in Table 1. Similar to the results presented in compression or split tensile strength, this table illustrates the detrimental effect of rubber particles on the flexural tensile strength of conventional concrete as well as different rubberized composites depending on the rubber incorporation rate. However, it can be observed that for all volumes of rubber particle incorporation, the flexural tensile strength of BCGC and BCPC composites exceeds 2 MPa, the minimum value required for usability in the design of rigid pavements (wearing course or foundation layer), according to the specifications of standard EN 13877-1. Fig. 4 depicts the loss rate in flexural tensile strength for all composites containing rubber particles of various granularities.

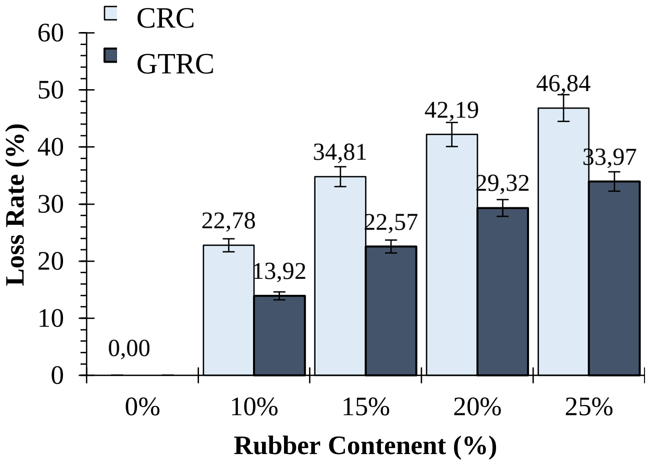

Fig. 4 Evolution of the loss rate in flexural tensile strength compared to conventional concrete for CRC and GTRC composites

Table 1. Results of the mechanical performance of the various rubberized composites

Specimens	f_{c28} (MPa)	Standard Deviation	f_{ct} (MPa)	Standard Deviation	f_{cf} (MPa)	Standard Deviation
CC	32.05	0	2.81	0	4.74	0
CRC10	25.07	4.93	2.09	0.50	3.66	0.76
CRC15	20.85	7.91	1.72	0.77	3.09	1.16
CRC20	18.52	9.56	1.52	0.91	2.74	1.41
CRC25	16.58	10.93	1.36	1.02	2.52	1.56
GTRC10	29.25	1.97	2.48	0.23	4.08	0.46
GTRC15	25.88	4.36	2.32	0.34	3.67	0.75
GTRC20	23.22	6.24	1.96	0.60	3.35	0.98
GTRC25	20.70	8.02	1.83	0.69	3.13	1.13

IV. DISCUSSION

While these elastomers disrupt the dynamics and proper development of mechanical strengths in rubberized composites, the indicators revealed by these tests underscore the importance of the shape and size of rubber particles when incorporated into a cementitious material, highlighting their direct impact on the progression of these mechanical properties [17]. Indeed, the deformability of rubber as well as the minimization of solid, rigid, load-bearing aggregates can be the limiting factor affecting mechanical properties and leading to the production of high internal stresses around these rubber particles. Additionally, referring to results reported in the literature, Benazzouk et al. observed in their experiments that the workability of rubberized concrete was strongly affected, which can be explained by the shape, texture, and non-polar nature of rubbers, capable of trapping air on their surface with a tendency to repel water [18]. This tends to increase the volume of voids in the matrix and thus weaken the mechanical strengths of the composites. Another study dealing with the properties of self-compacting concrete modified by rubber reported that the intensity of resistances can be affected by many factors such as the type of aggregates used, their particle size distribution, their distribution in the cementitious matrix, and the type of admixture used [19]. In fact, the polycarboxylate-polyacrylate copolymer of the superplasticizer admixture can cause the enlargement of ettringite and calcium hydroxide crystals and thus weaken the cement-aggregate bond, while high rubber contents lead to increased shrinkage resulting in microcracks in the interfacial transition zone (ITZ) and thus affecting the mechanical properties of the composites. Therefore, it can be concluded, as for compressive and splitting tensile strengths, that a high rubber content in a cementitious composite leads to a weakening of mechanical properties, conditioned by the degree of rubber incorporation into the cementitious matrix, but also by their morphologies. However, it should be noted that the distribution of rubbers, which is difficult to control in the cementitious matrix, can also play a role in the drop in mechanical strengths and mainly depends on a superplasticizer admixture acting as a stabilizer in a cementitious mix.

Various optical micrographs were taken to explain the decrease in mechanical characteristics of rubberized composites, whether in compression or tension. Indeed, the first assumption for the decrease in mechanical strengths in rubberized concretes is related to the low rigidity of rubber particles compared to natural aggregates, specifically sand in this present study. The second assumption is that the elasticity and deformability of rubber can be the limiting factor affecting mechanical properties, leading to interfacial bonding defects between elastomers and the cementitious matrix. Thus, under load, cracks initiate around rubber particles and accelerate failure in the overall matrix of the composites. It is also well-known that the mechanical strength of a material is opposed to its density. Furthermore, the more air voids present, the lighter the material, and the lower its mechanical strength. To validate this hypothesis, an interfacial transition zone (ITZ) between a rubber particle and the cement paste was observed using optical microscopy as presented in Fig. 5.

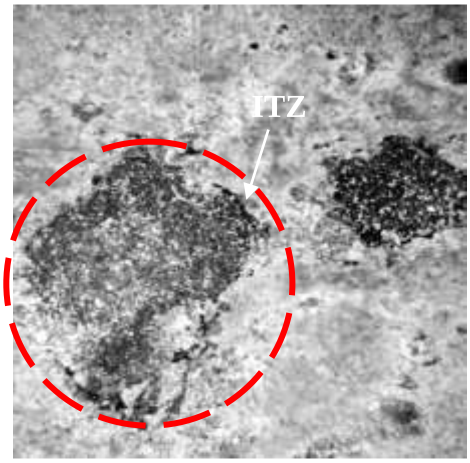

Fig. 5 Optical micrograph showing the Interfacial Transition Zone (ITZ) between rubber and cementitious matrix

In general, rubber particles have a smoother surface compared to natural aggregates, which may explain the poor adhesion with the cementitious matrix. The decreases in mechanical strengths in various composites can also be attributed to the fact that rubber is more deformable, leading to high internal stresses within the cement matrix. Fig. 6 illustrates an example of rubber particle distribution in the cement matrix following a rupture during a compression test.

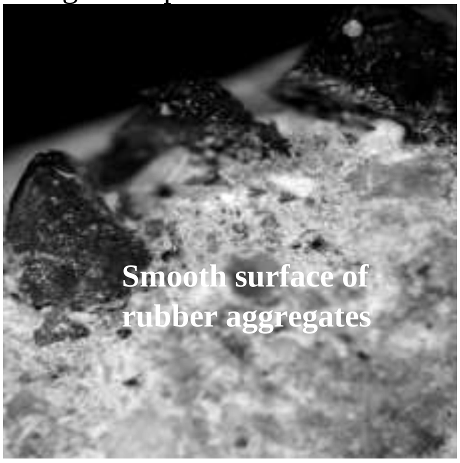

Fig. 6 Optical micrograph showing the smooth surface of rubber aggregates

Fig. 7 clearly shows the initiation of the rupture mechanism by the dissociation of rubber from the cement matrix. Indeed, under load, cracks are initiated around the rubber aggregates, accelerating the rupture of the internal structure of the composites and the cement matrix. Furthermore, as previously explained, these rubber particles act as voids in the matrix because they can be easily detached from the cement paste, thereby contributing to the increase in overall porosity with a consequent decrease in mechanical strengths of the composites. However, drawing inspiration from Desov's theory [20] and based on these arguments, a complementary viewpoint can be explored to explain this decrease in mechanical characteristics of rubberized composites. This theory considers that the rupture of concrete is conditioned by several combined effects such as the loading of the aggregates composing the concrete, the loss of adhesion between the aggregate and the cement paste, as well as the cracking of the cement paste or mortar between the aggregates.

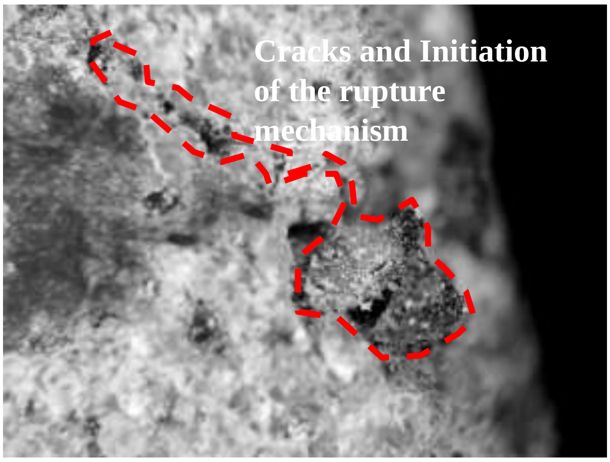

Fig. 7 Optical micrograph showing the initiation of the rupture mechanism and the propagation of cracks in the cement matrix around the rubber particles

V. CONCLUSION

Through the study of the mechanical characteristics of rubberized composites in relation to strengths and observations via optical microscopy, the following conclusion can be drawn:

A decrease in the mechanical strengths of rubberized composites compared to conventional concrete, as the rubber incorporation rate increases in the mixes, is primarily due to the low rigidity of the soft inclusions, as well as to interface bonding defects with the cement paste, revealing an increase in void volume attributable to this weak bond between these elastomers and the cement matrix. However, a less significant reduction in mechanical properties can be observed in the case of mixes based on smaller rubber particles, with a maximum loss rate estimated at 35.41% in compression, 34.88% in splitting, and 33.97% in flexion compared to a maximum loss rate estimated at 48.26% in compression, 51.60% in splitting, and 46.84% in flexion for composites based on coarser rubber granules. This indicator thus reveals the importance of the shape and size of rubber particles when incorporated into a cementitious material, influencing their adhesion and highlighting their direct impact on the evolution of mechanical properties.

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