Behavior of modified concrete based on crumb rubber: Experimental test and numerical investigation

Amar Mezidi¹, Ratiba Mitiche Kettab¹, Hamid Hamli Benzahar² and Mahfoud Touhari³

¹Department of Civil Engineering, National Polytechnic School of Algiers, Algeria
²Department of Technology, Faculty of Sciences and Technology, University of Khemis Miliana, Algeria
³Acoustic and Civil Engineering Laboratory LAGC, Faculty of Sciences and Technology, University of Khemis Miliana, Algeria

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Abstract. The Crumb rubber concrete is becoming a new interesting environmental material in the last two decades, which requires research studies on the recovery of local materials using industrial waste. The present paper is devoted to investigate the behavior of concrete made only with dunes sand and an ordinary concrete modified with various weight contents of crumb rubber. The mechanical and physical properties such as the density, the compressive strength, the relative compaction and the tension by bending strength of a dune sand concrete and an ordinary concrete modified with different weight percentage of rubber crumb, 1%, 2%, 3%, 4% and 5% are investigated. The obtained results show that the optimal percentage of the rubber crumb is 3%. In addition, the results indicate that concrete made only with dunes sand has weaker elasticity modulus -54% approximately, and reduced compressive strength -63% compared to the modified ordinary concrete. Consequently, the ordinary concrete mix with crumb rubber and admixture incorporation has proven acceptable performances for the eventual use in the structural elements, however, the dunes sand only aggregate concrete modified by crumb rubber may limit its use in certain structural applications such as pavements borders. Finally, modified ordinary concrete and modified dunes sand are modeled by the finite element method and compared with the experimental results.

Keywords: elasticity modulus; finite elements; materials mechanical behavior; modified concrete; rubber crumb

1. Introduction

Crumb rubber concrete, also called recycled tire rubber-filled concrete, is becoming a new interesting environmental material in the last two decades. More than 1.5 billion tires are produced worldwide per year, and most of these tires will sooner or later become waste (Xu et al. 2018, Karakurt 2015). Statistics indicate the increased consumption of rubber worldwide between 2000 and 2018, including natural and synthetic rubber. In 2017, combined global consumption of natural rubber and synthetic rubber totaled 28.4 million metric tonnes where different countries are facing growing problems for several years of disposal of these recycled materials. The disposal of tire waste becomes very expensive once it is sent to landfills. Not to mention the vast space they use for landfills and the risks they pose to the environment. In the other hand, the demand for building materials continues to increase year-over-year worldwide and is not being met due to insufficient supply. This imbalance, which seems to last for years, cannot be overcome without taking advantage of recyclable materials such as used waste tire rubber available in each country. In fact, the recovery of huge amounts of used waste tire rubber in the construction has a triple advantage: environmental, technical and economic. Along with the expansion of the concrete industry around the world, other industries have also made progress in this sector. One of the most important of these is the adjuvant sector. Concrete has acquired improved properties with chemical and mineral admixtures (Sahlocrete 1994, Festa 1998, Bravo and Brito 2012). They used tire rubbers as recycled material and replaced a portion of the fine aggregate with filtered used tire rubber powder to produce an ordinary concrete modified with crumb rubber OCR (Yung et al. 2013, Benbellil et al. 2018). Since ordinary concrete modified with crumb rubber (OCR) flows under its own weight, no external vibration is needed to compact the concrete. Ordinary concrete modified with crumb rubber OCR, as highly openable concrete, was introduced for the first time in the late 1980s in Japan (Youssf et al. 2016, Benouadah et al. 2017). OCR is characterized by its high pulp content and, as a result, various cement-based materials such as slag, natural pozzolana, limestone and metakaolin are added to the mixture (Yahiaoui et al. 2017, Morlier and Viguier 2000, Kettab et al. 2007, Tayeh 2013). Rubberized concrete studies show a reduction in unit weight and mechanical properties (compressive, tensile and flexural strength) and a more ductile behavior with increased rubber content (Khaloo et al. 2008, Kromoser and Huber 2016, Segre and...
Joekes 2000, Meddah et al. 2017). This paper examines the potential use of recycled rubbers in roller-compacted concrete pavements to improve performance and reduce environmental impacts, including the effects of adding low percentages of rubber particles to dunes sand only aggregate concretes (DSCR) and ordinary concretes. The relationship between the compaction force applied and the rubber content is determined, presented and detailed. There are several studies conducted on Crumb rubber concrete among them (Xu et al. 2018), for the numerical part, we devoted our study on the optimal percentage of rubber crumbs (3%) for the two concretes OCR and DSCR.

2. Material and methodology

2.1 Crumb rubber

The polymer used as modifier is crumb rubber which comes from the recovery of crushed rubber waste of soles of shoes and carpet of vehicles. The size of the crumb rubber used varies from 0.1 mm to 2 mm of fine powder (Fig. 1). Rubber waste is a huge recoverable pool, either by volume or by weight. The origins of this pool are worn tires; industrial rubber wastes, tires manufacturing wastes and retreading waste. Currently, 25% of rubber and tires are recovered, while there are a variety of treatment modes.

The polymer used in this work is a blackish industrial; resulting from the crushing of the rubber in fine textured form 1.25 mm maximum and 31%<0.08 mm (Fig. 2); with 45% of a waste purity. It is an elastic material at ambient temperature compatible with cement and aggregates. It has a low viscosity at high temperature with a melting temperature of 200 to 220°C. (Abdeldjalil et al. 2019).

The spectrum of infrared spectroscopy characterizing the polymer used is given in Fig. 3. The available spectrum indicates that the polymer is a rubbery material of the ABR (Butadien Rubber) type.

In Fig. 3, The FT-IR spectrum of the normal untreated sample containing rubber shows typical absorption bands from poly-butadiene (C-H stretching at 2919 and 2852 cm-1, -CH2 twisting at 1384 cm-1 and out of plane deformation of C-H at 867 cm-1) and from polystyrene (aromatic C-H stretching at 3014 cm-1, aromatic C=C stretching at 1631 cm-1) units. There is also C-O-C bending absorption at 1122 cm-1. Finally, band detected at 539 cm-1 corresponds to the stretching mode of Zn-O single bond. These results confirm that the sample analyzed by FTIR is probably constituted by styrene-butadiene-styrene rubber compacted with zinc oxide. In order to identify the chemical composition of the waste, a microanalysis was carried out. Indeed the punctual analysis by EDS measures the relative composition of organic matter and minerals. The microstructure of the waste was observed using a Jeol-type scanning electron microscope (SEM), JSM-6360 LV. The results are shown in Fig. 4.
The morphology of the rubber (Fig. 4(b): view of the surface) shows that this material exhibits heterogeneous dense structure, the distribution of the different components is not uniform. We note also that a grey color is recognized to the rubber polymeric chains and the white color is attributed to zinc grains (Ketta, et al. 2004, Lyacia et al. 2019). The density of this material is 1.22 measured relative to ethanol, which has a density of 0.79. The physical properties of the rubber crumb are summarized in Table 1.

2.2 Aggregates

Table 2 and Table 3 summarizes, respectively, the basic chemical analysis and the main physical properties of aggregates 3/8 and 8/15. The important values of the soluble ratio (carbonates-CaCO3) in the analyzed gravel samples with respectively 85.47% and 89.74% indicate that these two gravels have a calcareous character.

Table 4 and Table 5 summarizes, respectively, the basic chemical analysis and the main physical properties of dunes and natural sands. The important values of the ratio of insoluble materials (silica SiO2+silicates) in the analysis are respectively 94.86% for dunes sand and 86.07% for natural sand, indicating that these two materials have a siliceous character.

The mixing water used for the manufacture of concrete is water tape without additional treatment and does not
contain excessive harmful substances such as salts, sulphates and acids. The adjuvant used is the Medaflow SR20 super plasticizer, a 3rd generation water reducer. It is made from a polycarboxylate base that significantly improves the properties of concrete and gives concrete and mortars of the highest quality. The super plasticizer content varies from 1 to 2.5% of the weight of the cement. For cement, CPJ CEM II / A 42.5 NA 442 composite Portland cement was used.

3. Experimental design and procedure

3.1 Preparation of mixture concrete

In this section, the mixtures concrete of Ordinary Concrete Modified by Crumb rubber (OCR) and Dunes Sand only aggregate Concrete modified by Crumb rubber (DSCR) are studied. The amount of rubber is incorporated into the sand for both concrete OCR and DSCR. We prepare at the star Pilot control samples containing 0% rubber, the other samples containing 1%, 2%, 3%, 4% and 5% of rubber (The quantity of rubber is incorporated in the percentage of sand by weight). Table 6 presents the mixer formulation of both concrete OCR and DSCR with different amount of rubber crumb.

3.2 Procedure of control

The hardened concrete tests of OCR are the compressive strength, the tension by the bending strength, and the concrete relative compaction test. Concerning the compressive strength test, the measurement was carried out on 100 mm cubic samples at the age of 7, 28 and 90 days for all the rubber contents. The aim was to assess the change in compressive strength depending on the age of the concrete and the rubber content. The tension by the bending strength, measurements were made on prismatic specimens (70x70x280) mm³. The test was carried out at 28 days to observe the variation of the concrete’s tension by bending strength against various rubber contents.

Fig. 5. In order to properly simulate the behavior of DSCR, Prismatic specimens of dimensions (40x40x160) mm³ were adopted for all compositions for measure the tension by the bending strength. The compressive strengths are obtained by crushing the cubes of dimensions (40x40x40) mm³. The specimens were cured in water for 28 days at a constant temperature of 25°C.

4. Results and discussions

4.1 Slump test and workability

Slump test and density measurements were performed on each concrete mixture. The slump test of OCR results are summarized in Table 7. This table shows that the measured slump increases with the rubber content. In fact, rubber is coarser than sand and will therefore absorb less water.

The workability of DSCR with different rubber contents is summarized in Table 8. The results show that the
workability of DSCR is improved by increasing the rubber content, which can be justified by the low adsorption of water by the rubber particles, which saves a certain amount of mixing water for other concrete components without varying the ratio W/C, (W/C remains fixed=0.69).

4.2 Density

The density concrete values measured for both type concrete OCR and DSCR with different rubber contents are shown in Fig. 6. The results indicate that the concrete density is inversely proportional to the rubber content. This can be explained by the fact that the rubber density (0.54 t/m³) is considerably smaller than sand’s density (2.56 t/m³). Due to its fine texture, sand dunes only aggregate concrete is lighter than ordinary concretes. The higher the crumb rubber content, the lower the concrete density. The addition of crumb rubber will lighten strongly the DSCR compared to OCR. This is to be interpreted by the large quantity of sand incorporated in the DSCR compared to the OCR. Knowing that the percentage of the crumb rubber is a function of the quantity of sand, for example, for 3% of crumb rubber, the quantities of sand reduced for OCR and DSCR are respectively 47 kg and 16 kg for 1 m³ of concrete, approximately one third (1/3). In addition, it can be noted that the density decreases in an almost linearly.

4.3 Compactness

The Fig. 7 shows the OCR and DSCR relative compaction with different rubber content. It can be seen that the concrete relative compactness of OCR increases from 0 to 1%. The intergranular interstices of the aggregates are progressively occupied by the rubber loads; the volume has been reduced, which slightly increases the settlement between 1% and 5% and most interstices are already filled.

Thus, it can be said that the relative compactness stabilizes above 1%. The handling is improved when the rubber content is increased. This is due to the low adsorption of water by the rubber particles, which saves a certain amount of mixing water for the other constituents of the concrete without modifying the water / cement ratio (W/C=0.51).

By gradually increasing the rubber content from 0 to 5% in increments of 1% step, it can be seen that the concrete relative compactness of DSCR shows significant increases at the 1% stage. The inter-granular aggregates gaps were occupied by rubber fillers decreasing so the gaps volume which increases the relative compaction in a lightly noticeable way between 1% and 4% as most of the gaps were already filled. Thus, it can be said that the relative compactness stabilizes above the rubber content of 1%.

4.4 Compressive strength

At this step of measurement, the OCR and DSCR compressive strength were determined according to EN 12390-3, using a 2000 kN capacity hydraulic press machine with an applied loading rate of 0.5 MPa/s. The average values of three cubic specimens at three different ages 7, 28 and 90 days were recorded. The results of the compressive strength tests conducted on the OCR and DSCR mixture.
studied are given in Fig. 8. According to this figure, the compressive strength is inversely proportional to the rubber content; the more increased the proportion of rubber, decreased the compressive strength. For a rubber content of 4%, the concrete compressive strength of OCR and DSCR represents respectively 45% and 39% according to the pilot’s concrete strength. This is due to the low intergranular cohesion favored by the rubber particles. For the rubber content of 3%, the compressive strength obtained represents a significant percentage of 63% at 28 days and 60% at 90 days of the concrete strength for OCR and 46% at 28 days and 49% at 90 days of the concrete strength for DSCR.

4.5 Tension by bending strength

Fig. 9 shows the reports between the tension of OCR and DSCR concretes and the tension of the pilots concrete according to the rubber content. It can be seen from this figure that the tension by bending strength is inversely proportional to the rubber content. For example, a rubber content of 4%, the strength represents, respectively, 35% and 43% of OCR and DSCR of the witness concrete. This is due to the poor intergranular cohesion favored by the rubber particles. Whereas for a rubber content of 3%, the tension by bending strength represents an interesting percentage of 60% and 54%, respectively, for OCR and DSCR of the pilot concrete strength.

The analysis results of the compressive and flexural tensile strength tests allow concluding that the content of 3% of crumb rubber introduced is an interesting percentage. This rate of 3% can be considered as an optimal rate

4.6 Concrete behavior in compression

The objective of this part is to study the relationship between the modulus of elasticity and the characteristic strength of concrete and to trace the stress-strain curves in the case of Ordinary Concrete Modified by Crumb rubber (OCR) and Dunes Sand only aggregate Concrete modified by Crumb rubber (DSCR). For the quantification of the elasticity modulus, various construction codes suggest a relationship to the power of 1/3 of the breaking strength of the concrete. BAEL 91 Rules are applicable to sand dunes only aggregate concrete when the artificial portland cement content is greater than 300 kg/m³. Cubic specimens of dimensions (150×150×150) mm³ are used for the optimal compositions. These test pieces were then subjected to extensometry tests, allowing the determination of longitudinal and transverse deformations as well as that of the modulus of elasticity (Young's modulus). Sand dunes only aggregate concretes are more deformable than classic concrete. The instantaneous deformation modulus can be estimated using the formula (Bobinski and Tejchman 2007):

For sand dunes only aggregate concrete

\[ E_{id} = 8100 \times f_{cd}^{1/3} \]  

(1)

For a classic concrete

\[ E_{id} = 11000 \times f_{cd}^{1/3} \]  

(2)

Where 'd' is the concrete age by day. The differed deformation modulus can be deduced by the formula

\[ E_{vd} = \frac{1}{3} E_{id} = 2700 \times f_{cd}^{1/3} \]  

(3)

With: \( E_{id} \) Instant Elasticity Modulus, \( E_{vd} \) Delayed Elasticity Modulus, \( f_{cd} \) Compression strength to \( D \) days

In the present study, relative strains have been measured...
under load in order to assess the behavior: low (stress-strain). Here, 150 mm-cubic test pieces fitted with electrical wire gauges that measure the strains in two directions (longitudinal and transversal) have been used (Hosseinpour and Abbasnia 2014). These tests consisted in applying a 20 kN incremental compression load at an average speed of 15 kN/s. For each load increment, the longitudinal and transversal strains are recorded. The tests were performed on DSCR 3% and OCR 3% mixtures.

5. Numerical modeling

Based on the behavior of modified ordinary concrete and modified dunes sand concrete, experimentally determined, both types of concrete can be modeled. The numerical analysis is mainly based on ordinary concrete (OCR 3%) and dunes sand (DSCR 3%). The numerical model is a prismatic specimen (150×150×150) mm³, subjected to compressive and tensile stress tensile ranging from 0 to 30 MPa (Hamid 2019). According to the experimental analysis, the elasticity modulus of OCR 3% is $E_1=23342$ MPa and that of DSCR 3% can be $E_2=12748$ MPa, the Poisson’s ratio ($\nu$) is taken equal to 0.2. The numerical model of the specimen is discretized by finite elements using the software ABAQUS. The figure 10 represents the discretization of the analyzed numerical model.

By varying the compressive stress applied to the specimen of OCR 3%, whose elasticity modulus ($E_1$) and poison ratio ($\nu$) equal respectively to 23342 MPa and 0.2. The maps of the following figures represent the longitudinal distribution strain generated by the compressive stress.

On the other hand, numerical analysis requires the modeling of DSCR 3% having a elasticity modulus ($E_2=12748$) and a Poisson ratio ($\nu=0.2$) with various applied constraints to the specimens, the longitudinal distributed strains of this type of concrete are represented in the following figures. By applying the tensile constraints on the prismatic specimen (70×70×280) mm³, the following table groups the numerical values longitudinal strain of two types of concrete modified (OCR 3% and DSCR 3%).

According to the numerical and experimental analysis of ordinary concrete and dune sand concrete, the following figures represent the stress-strain curves.

6. Results and discussions

• The representative stress-strain curves for each series showed a typical three stage.  
  - 1st Stage: an almost linear elastic behavior of the concrete. For the DSCR, this stage corresponds to an elastic deformation $\epsilon_{el}=0.42\%$ which a stress of $\sigma=5$ MPa (55% of the one-axial stress) whereas for the OCR it is equal to $\epsilon_{el}=0.38\%$. The gradient at this curve origin is the longitudinal deformation modulus at the origin.  
  - 2nd stage: this stage is characterized by a parabolic shape of the longitudinal stress-strain curve up to a threshold corresponding to the maximum stress of each specimen.  
  - 3rd stage: this stage is characterized by a generalized cracking. The strain increases while the failure stress decreases. This phenomenon is observed on the longitudinal stress-strain curve of both concretes as a downward branch of which the slope represents the more or less marked brittle nature of the concrete. The dunes sand only aggregate concrete is less brittle since this slope is practically horizontal while it is almost vertical for the ordinary concrete which reflects it brittleness.  
  • The longitudinal strain modulus at the origin is given by the tangent to the longitudinal stress-stress curve. For OCR 3%, $E$ was found to be 23342 MPa, while for the DSCR mixture at 3% rubber, $E=12748$ MPa. The
elastici ty modulus of dunes sand only aggregate concrete is apparently small compared to ordinary concrete.

- Finally, a numerical verification is carried out by implementing non-linear Finite Element Analysis (FEA) using ABAQUS software. The reliability of the FE
models is demonstrated by a comparison with the experimental results, which shows good agreement of both types of modified concrete (OCR and DSCR) in terms of stress-strain curves and failure load of two concretes with optimal rubber content (3%). Therefore, ABAQUS software can be used to predict the capacity of the modified concrete with rubber crumbs on the construction sites while respecting the optimum of the crumb rubber demonstrated in the experimental study (3%).

7. Conclusions

The work presented in this study focuses on the possibility of using the crumb rubber in the ordinary concrete and Dunes Sand only aggregate Concrete the dunes sand only aggregate concrete. The incorporation of crumb rubber into dunes sand only aggregate concrete (DSCR) represents a dual opportunity: the first is the value enhancement of sand dunes, which represents a significant percentage of local materials in some countries of the world and the second is the recovery the waste resulting from wounded tires which are present in high non recovered quantities. This opportunity can potentially solve a triple problem: environmental protection by reducing waste storage areas and the resulting contamination, economic and technical issues encountered in the construction fields due to the scarcity of building materials.

The experimental study of the tested mixtures has shown that the addition of small percentages of rubber to sand dunes only aggregate concrete and ordinary concretes is not recommended if the strength is the main objective. However, a well chosen amount of additives often leads to improve the characteristics and properties of the mixtures, an excess can sometimes lead to the contrary. Therefore, it can be concluded from the present study that:

- The ratio 3 is the optimal that has a significantly amount of usable rubber waste, while preserving the main characteristics of the concrete compared to the 4 and 5% where the concrete has a significant loss of these properties.
- Owing to its small particle size distribution, dunes sand only aggregate concrete is lighter than ordinary concrete. Adding the crumb rubber will even lighten them because of the introduction of rubber particles with porous structure in a heavier and denser cement matrix. This decrease is almost linear.
- The workability is improved when the rubber content is increased. This aspect is explained by the weak water absorption by rubber particles which saves a certain amount of mixing water for other concrete constituents; (Topçu and Bilir 2009, Hilal 2017).
- The compressive strength decreases as the incorporated rubber content increases;
- Mechanical properties of dunes sand only aggregate concrete modified concrete compared with those of ordinary one with the same rubber content are not in favor of using it in structural elements. Nevertheless, dunes sand only aggregate can be used as a material for pavement borders, decorative elements, roads separation in motorways...

- A good agreement was obtained between experimental and proposed model results

References


Sablocrete (1994), Beton de Sable, Presse de L’Ecole Nationale des Ponts Et Chaussees, Paris, France.


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