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# Mechanical and environmental study of the valorization of waste tires in bituminous concrete applied in Tunisia

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**Abstract**

Given the increase of Tunisia's car fleet and the high utilization of tires, waste production has risen sharply, causing enormous economic and environmental problems in this country. Our research team is in the process of developing different axes of valorization of this waste tires crumbs from the perspective of the field of civil engineering. This work presents the first results of the valorization in the road surface by producing a bituminous concrete (BC) containing aggregates coming from waste tires (crumbs). This study is carried out using the aggregates of DJebel El Oust showing that the addition of the rubber crumb reduces the mechanical strength, and on the other hand, the compactness increases and the resistance to water is improved. An environmental study was conducted on the modified bituminous concrete mixed with waste tires crumbs. It is recommended that in order to reduce the environmental impacts, the modified bituminous concrete is best used on acid Tunisian soils located mainly in the extreme North West region of the country.

*Keywords*: Waste of tires crumbs; Asphalt; Aggregates; Strength; Stability Marshall; Compactness; Water resistance

## 1. Introduction

Every day millions of tires are generated due to the growing use of vehicles in developed countries. So, each year 1.4 billion tires are bought which implicates that 1.4 billion tires become end of life types tires (ELTs), the growing traffic in US, Europe and Japan, makes the number of ELTs grow each year. Due to their durability, these tires are one of the most harmful wastages in the environment.

According to US environmental protection agency 45 million out of 290 million of the scrap tires were used to make automotive and truck type re-treads [1].

Europe represents 24% of the world's tires production [2] with an estimation of 5.5 million tons of illegally disposed tire's stockpiles and 600 million Euros of management cost [3]. These numbers show the raising threat on human health and the environment. This is why, many countries banned the disposal of tires [1].

The continuous growth of the car fleet in Tunisia generated 25000 tons of used tires in 2005 and will exceed 2.5 million units in 2025 (waste management national agency, Tunisia). For this considerable production, an environmental management problem arises. Its valorization leads to the protection of the environment and minimizing of the costs of storage and reuse.

The tires are essentially made of an elastomeric compound. The flesh, fabric and steel and the structural skeleton [4] represent a high-tech safety product. By a specific engineering process the rubber can easily deform when heated up and brittle when cooled down. The improvement of the rheological properties of tires viscosity and the better mechanical performance, especially the aging resistance, is the outcome of the addition of the tires and the increase of the thickness which are automatically related to fatigue, cracking and plastic deformations [5,6].

These properties make the use of crumb rubber modifier from scrap tires the most used in hot bituminous mixes for the road construction [7-13]. The process of adding a crumb rubber modifier contributes to the sustainable development involves automatically the valorization of waste materials and reduces their volume at landfills. It also reduces the noise level of the road surface coarse and guarantees more safety thanks to its long-term color contrast. Two processes have been used to

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incorporate crumb rubber in asphalt paving since1960s.The wet process and the dry process [14].The wet process, have shown better results making it more popular then the dry method in many countries. For the wet process the studies focused on the optimization of the characteristics of the crumb rubber and bitumen, temperature and time of mix [15-17].

As for the dry process the main focus was on the digestion time, manufacturing time, as well as the size and the quantity of the crumb rubber added [18-23].

Tow states in Australia are using the wet process especially for sprayed seal application. As for some regions in Europe the wet rubberized asphalt is used in road pavements applications such as France and Germany ... [24-27]. The leading countries applying this method are Portugal, Spain, Italy, Czech Republic and Sweden and now it is more and more used worldwide [28-32].

The viscoelastic behavior of the rubber as well as its damping potential, promote a better functioning in dynamic conditions [33].

The tires have an ignition temperature of about 338 ± 8°C and an auto-ignition temperature of about 465 ± 8°C [34]. This is not a risk since the temperature of manufacturing and using bituminous concretes is 150-180°C. Research has shown that incorporating 2% of recycled rubber crumbs improves sound and acoustic characteristics in low frequencies [35] as the introduction of rubber aggregates into the concrete significantly reduces the speed of ultrasonic waves. According to Albano et al. [36], the size of the rubber aggregates (G.C) considerably influences this kinetic since the smaller the G.C. size, the lower the speed.

According to H.T.Tai Nguyen & al [37], tires crumbs contribute to significant improvement in the rutting resistance of bituminous concrete. Moreover, studies have been carried out to quantify the toxicity risks of smoke emissions [38]. The quantities of pollutants identified in the emission of fumes for a rubber containing asphalt mix are equivalent, or even less than that of a pure bitumen mix [39]. On the other hand, Haddadi et al. [40] worked on polymeric bitumen incorporating rubber crumbs having diameters Ø ≤ 0.2 mm in dispersion in the bitumen with hot stirring. Table 1, summarizes the tests on bitumen modified by different grades of rubber crumbs.

They noted a remarkable improvement at penetrability and at the softening temperature Ring ball for high additive levels. This contributes to the improvement of the viscoelastic behavior of the modified bituminous concrete (BC). According to OuldHenia [41], the results of the fatigue test show that the laboratory bending fatigue lifetime of rubber-based bituminous concrete is increased to 2-10%.

In this work, With the collaboration of the company Ecopneu (supplier of tire crumbles located in Sidi Elheni governorate of Sousse in Tunisia) that provided us the waste tires of different grain sizes, we were able to do the tests of characterizations and mechanical performances on the mixtures at the test center and construction techniques in Tunisia (CETEC). We will study for the first time the valorization of tire crumbs in the BC 0 /1 4 ( the grain size skeleton was mostly composed of 4/14 mm coarse aggregate (53–65% of the total) to provide the mix with bearing capacity. The rest of the mixes were composed of 0/4 fraction of fine aggregate (35–47% of the total), with which the bitumen and the filler (4.7–5.3%) made up the mortar that made the mix cohesive and provided it with resistance to tangential) using local aggregates from the DJebel EL Oust (Governorate Zaghouan Tunisia) site in solve an environmental problem major in Tunisia.

First, We will study the effects of the addition of waste of tires crumbs in the formulation of bituminous concrete BC 0/14 on the mechanical performance, namely the compressive strength and water sensitivity (Duriez Test) , the compactness, stability and creep (Marshall test) starting from a reference mixture noted M0.This does not include the incorporation of waste of tires crumbs and five other mixtures with waste of tires crumbs proportions varying from 0.7% to 7% rated M1, M2, M3, M4 and M5. Once the optimal formulation is mechanically validated the second step is the environmental validation. An evaluation of conductivity, TDS (total solids dissolved as a function of PH), Biochemical oxygen demand (BOD), and chemical oxygen demand (COD) were also conducted to investigate the impact of bituminous concrete with waste of tires crumbs on the environment and define the most favorable environment for the use of tires waste in BB 0/14 knowing that Tunisia is divided into two zones (zone I acid pH 5 to 6 and zone II pH basic from 7.5 to 9, Fig. 12).

Table 1
Influence of rubber crumb content on bitumen characteristics [39].

| Rubber crumb content | | 0% | 3% | 5% | 7% | 10% |
|---|---|---|---|---|---|---|
| Before RTFOT | Penetrability (1/10mm) | 44 | 30 | 29 | 26 | 22 |
| | TBA (°C) | 52 | 57 | 57 | 58 | 60 |
| After RTFOT | Penetrability (1/10mm) | 29 | 16 | 15 | 14 | 14 |
| | TBA (°C) | 61.9 | 69 | 69 | 70 | 74 |

## 2. Methods and characterization of materials used.

### *2.1. Methods*

The experimental method of formulation adopted by the CETEC is based mainly on the choice of the used materials which must satisfy the physicochemical properties and the mechanical performances fixed in the specifications CCTP (special technical clause booklet applied by the Ministry of equipping and Tunisian housing) namely the hardness, the cleanliness, the angularity, the shape, sand equivalent test and specific gravity.

Once this choice is made, a granulometric analysis of each granular fraction (crushing sand 0/4, gravel 4/8, gravel 8/14 and tires 0.5 / 3) will be developed. The combination of the different sizes of aggregates must obtain a mixing curve with a result between two upper and lower limits, thus, constituting the standardized spindle of a bituminous concrete BC0 / 14 (conforming to CCTP).

### *2.2. Characterization of materials used.*

#### *2.2.1. Crushed aggregates.*

The aggregates used for the formulation of bituminous concrete BC 0/14, are composed of three granular fractions which are crushed sand 0/4, gravel 4/8 and gravel 8/14. Fig. 1 shows the granulometric curve of these three aggregates [42].

These are class C limestone aggregates. The curve has a spreading particle size for sand 0/4 and tightened for gravels 4/8 and 8/14.

Table 2 shows a variety of fundamental engineering characteristics of the aggregate used in this research, according to the standards mentioned.

The shape coefficient A is less than15, so the aggregates do not present a risk of slippage. The aggregates used must comply with the following specification: LA ≤ 25, MDE ≤ 20, PS ≥ 45 (Threshold required by the CCTP for a BC 0/14).The values found by the sand equivalent test and Micro-Deval test meet the values required for the bituminous concretes (BC). On the other hand the value LA % is approaching the norm but still insufficient.

### 2.2.2. *Tires crumbs.*

The tires crumbs used in this work were supplied by the company ECOPNEU located in Sidi Elhéni Governorate of Sousse. The crumbs obtained by mechanically grinding used but not recycled tires and (UTNR) the various residues (steel wires, rods, textile, etc.).Fig. 2 shows the granulometric curve of the tires crumbs. Our aim is to substitute a part of the crushing sand 0/4 by tires crumbs in order to recover them in the formulation of the bituminous concrete BC 0/14.

### 2.2.3. *The Bitumen.*

Bitumen is a hydrocarbon binder and is used to bond the aggregates to each other by developing cohesive forces within the mixture that provide stiffness, resistance to tensile deformation, compressive strength, and Shear strength [49]. The bitumen gives the bituminous concrete viscoelastic properties; it is also thermo-susceptible- its stiffness depends on the temperature [50]. The bitumen used in this study is a bitumen class 35/50, which is most commonly used in pavements. (Supplied by the company BITUMED located at the port of Radès whose characteristics are summarized in Table 3). The results of characterization of the hydrocarbon binder show that the bitumen used satisfies all the criteria of rigidity, resistance to permanent deformation and resistance to aging.Table 3 shows the specification required by the CCTP.

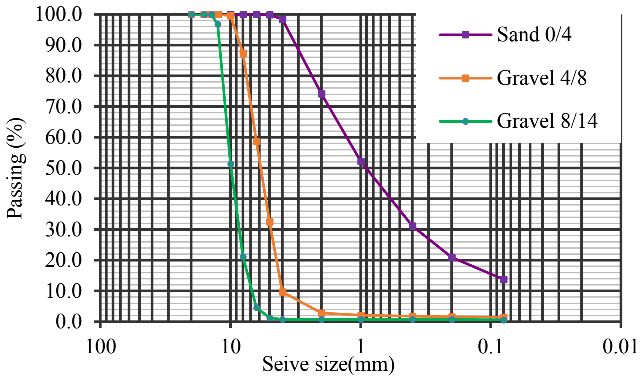



Fig. 1. Granulometric curve of crushed aggregates. (DJebel EL Oust).

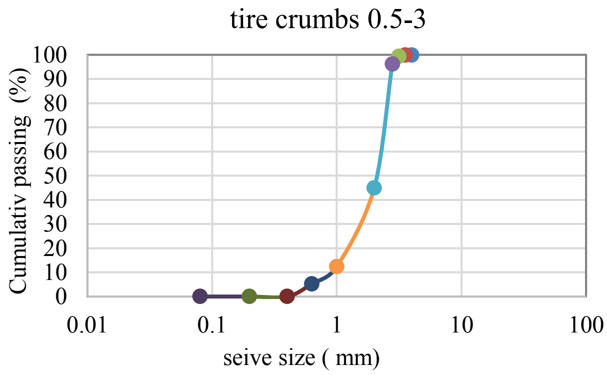



Fig. 2. Particle size distribution of 0.5/3 tires crumbs.

## 3. Formulation study

According to the Public Procurement CCTP, the BC 0/14 used in the rolling layers of flexible pavements must comply with the well-defined technical specifications (LA, MDE, ...).

Table 2
Identification of characteristics of aggregates of DJebel El Oust.

| | Shape coefficient A (%) [43] | Actual density (MVR) (t/m$^3$) [44] | Bulk density (MVA) (t/m$^3$) [45] | Sand equivalent test at 10% fine sand (ES) (%)[46] | Los Angeles (LA) (%) [47] | Wet Micro-Deval (MDE) (%) [48] |
|---|---|---|---|---|---|---|
| Sand 0/4 | - | 2,71 | 1.63 | 83 | - | - |
| Gravel 4/8 | 13.1 | 2,64 | 1.42 | - | 29 | 19 |
| Gravel 8/14 | | 2,67 | 1.38 | - | | |
| Tires crumbs 0/0.4 | - | - | 0.55 | - | - | - |
| Tires crumbs 0.5/3 | - | - | 0.5 | - | - | - |

Table 3
Characterization of bitumen 35/50 used.

| Testing | units | Required results * | Results |
|---|---|---|---|
| Needle penetration (EN1426) | 1/10mm | 35 à50 | 43 |
| Softening temperature ball ring TBA(EN 1427) | °C | 50à58 | 54,6 |
| Flash point (Méthode Cleveland en vase ouvert EN 22592) | °C | >240 | >250 |
| Resistance to hardening à163°C RTFOT (EN 12607-1) | | | |
| - % change in mass, | % | <0.5 | -0.05 |
| - % of remaining penetration after curing | % | >53 | 68 |
| - softening point after | °C | >52 | 58,2 |
| - increase in the softening point | °C | <8 | 3,6 |

*CCTP specification

We mix the four materials from a granulometric analysis of each granular fraction (sand0/4,gravel4/8, grave 8/14 and tires crumbs0.5/3) to obtain an optimum curve within the reference spindle of BC 0/14. The optimal curve is obtained on minimizing the gap between the averages of the grain size of the zone. Fig. 3 shows the granulometric curve obtained for the reference mixture M0.

The percentages obtained are, sand 0/4: 42%; Gravel 4/8: 28%; Gravel 8/14: 30%.

In order to determine the binder content (TL), a series of tests with different formulations were carried out. Starting from a reference mixture marked M0 where the granular fractions (sand 0/4, gravel 4/8, gravel 8/14) are mixed in spindle BC0/14 and not the incorporation of waste tires crumbs. The other five blends are obtained by adding proportions of tires crumbs ranging from 0.7% to 7 %.The proportions of the mixtures M1, M2, M3, M4 and M5 are summarized in Table 4.

In order to improve the mechanical properties of BC 0/14, and to correct the particle size of the mixture in the range 0/4 a tires crumbs (0/0.4 and 0.5/3) were used.

## 4. Mechanical study

### 4.1. Duriez test.

The test sets are used to determine the physical and mechanical properties of bituminous mixtures, especially for the water sensitivity (r/R) of bituminous specimens.

In order to study the evolution of the compressive strength and water sensitivity of BC 0/14 six granular mixtures containing three different levels of binders were prepared in accordance with the standard [51].

1. Let R: Compressive strength without immersion in water Preserved at 18°C.
2. Let r: Compressive strength after immersion in water for a duration of 7 days.

Three sets of 6 test pieces were prepared. A portion of these test pieces was preserved without immersion at a temperature of 18°C, while the other part was kept immersed in water. Two test pieces for each series were used for the measurement of the density by hydrostatic weighing to calculate the percentage of vacuum. Table 5 summarizes the Duriez (R) compressive strength for different granular mixtures (M0, ..., M5) and different binder contents (TL: 4.7%, 5% and 5.3%).

Fig. 4 shows the variation of the Duriez (R) compression strength as a function of the percentage of tires crumbs. There is a decrease of about 40% of the mixture resistance (M5) incorporating 0.7% of the tires crumbs 0.5/3 mm without falling below the minimum threshold required by the CCTP for a BC 0/14 which is 7 MPa.

Table 4
Composition of the mixtures tested.

| Mixture | Sand 0/4 (%) | Gravel 4/8 (%) | Gravel 8/14(%) | Tires 0,5/3(%) | Tires 0/0,4 (%) |
|---|---|---|---|---|---|
| M0 | 42 | 28 | 30 | 0 | 0 |
| M1 | 35 | 28 | 30 | 5 | 2 |
| M2 | 42 | 25 | 28 | 3 | 2 |
| M3 | 44 | 25 | 28 | 3 | 0 |
| M4 | 44 | 25 | 30 | 1 | 0 |
| M5 | 47 | 15,3 | 37 | 0,7 | 0 |

Table 6 summarizes the values of the water sensitivity ratio (r / R) of the bituminous mixtures for three different contents of binder.

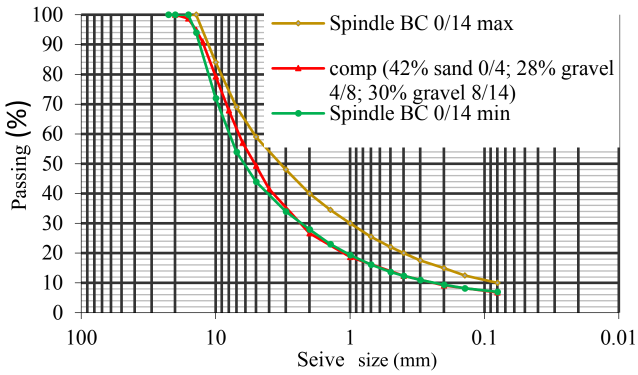



Fig. 3. Granulometric curve of the reference mixture M0.

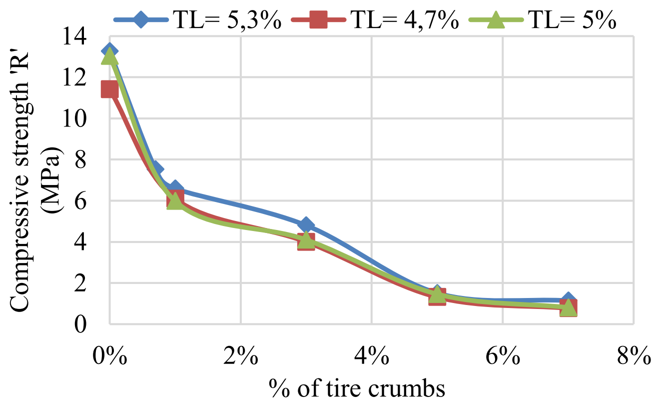



Fig. 4. Evolution of resistance R as a function of Percentage of tires crumbs.

Table 5
Variation of resistance R as a function of the addition of waste of tires crumbs.

| Resistance 'R'(MPa) | | | |
|---|---|---|---|
| Nature of the mixture | TL= 4,7% | TL= 5% | TL= 5,3% |
| M0 | 11,4 | 13 | 13,3 |
| M1 | 0,77 | 0,8 | 1,1 |
| M2 | 1,3 | 1,4 | 1,5 |
| M3 | 4 | 4,1 | 4,8 |
| M4 | 6 | 5,98 | 6,59 |
| M5 | - | - | 7,5 |

Table 6
Evolution of the water sensitivity r / R as a function of the additive tire.

| Water sensitivity ratios (r/R) | | | |
|---|---|---|---|
| Nature of the mixture | TL=4,7% | TL = 5% | TL =5,3% |
| M0 | 0,81 | 0,82 | 0,91 |
| M1 | 0,92 | 0,61 | 0,89 |
| M2 | 0,88 | 0,70 | 0,93 |
| M3 | 0,84 | 0,89 | 0,86 |
| M4 | 0,82 | 0,95 | 0,95 |
| M5 | - | - | 0,93 |

Fig. 5 shows that mixtures with tires crumbs have better water sensitivity ratios (r / R).

Compared to traditional mixes, the maximum value reached 0.95 for the mixture M4, there is less risk of disintegration. The decrease in the resistance of the mixture M3 to water is due to the low value of bulk density (MVA) of the test piece. It is well noted that the r/R ratio, for all the series, are close to 0.75, which corresponds to the minimum value required by the CCTP for a BC 0/14.

*4.2. Marshall test: French standard.*

In order to study the compactness and the creep of the mixture BC 0/14 with the incorporation of tires crumbs, we made samples according to the standard NFP 98-251-2, [52]. These tests were carried out only for a binder content of 5.3%.

*4.2.1. Influence of tires crumbs on density*

It is noted that the bulk density decreases as the percentage of waste of tires crumbs increases. This reduction reaches 15% for a substitution rate of 7% of the incorporated waste of tire crumbs.

*4.2.2. Measurement of compactness:*

The achievement of good mechanical performances requires optimizing the compactness of bituminous mixes. It represents a parameter of resistance to rutting.

Fig. 7 summarizes the different compacted values obtained as a function of the content of tires crumbs incorporated in the mixtures for the same binder content TL = 5.3%.

The graph shows that the mixtures with the tires wastes have better compactness that exceeds the 100% as a result to the incorporated 7% of the tires wastes, which shows that the addition of tires can act as a vacuum reducer.It is well noted that the compactness, for all the series, corresponds to the minimum value required by the CCTP for a BC 0/14. (Compactness: 92% ≤ C% ≤ 97%)

*4.2.3. Measurement of the Marshall stability of mixtures:*

Fig. 8 shows the variation of the Marshall stability as a function of the percentage of tires crumbs.

The stability decreases considerably with the addition of waste of tires crumbs compared to the reference mixture without any addition M0. It tends to improve gradually by decreasing the crumbs content of tires up to 0.7% but still it remains below the stability of the reference mixture M0. According to H.T.Tai Nguyen and T. Nhan Tran [37], the values of Marshall Stability can increase by nearly 70% when the curing time increases from 1 to 5 H. The work of Heznandez-Olivares and al, [38] was just limited to 2 h, and 1.5 h was found to be the optimal curing time.

*4.2.4. Measurement of creep Marshall:*

An increase in creep for mixtures incorporating waste of tires crumbs was also observed. At the exception of the M3 mixture that slightly exceeds the limit value, the other mixture remains below the limit value recommended by the CCTP (Creep: f ≤ 4 mm).

Mechanically the M5 mixture proved to be valid to the CCTP exigency, for the rest of the study the mixtures M0 to M5 will be analyzed to observe the environmental impact

The M4 mixture with 1% of waste will be analyzed for different waste percentages to investigate the environmental impact.

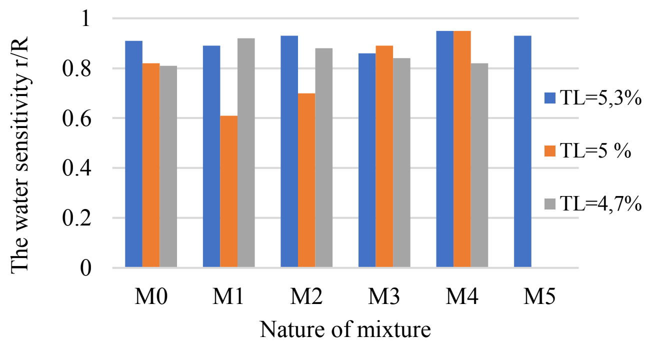



Fig. 5. Evolution of the water sensitivity (r / R) as a function of the Percentage of tires.

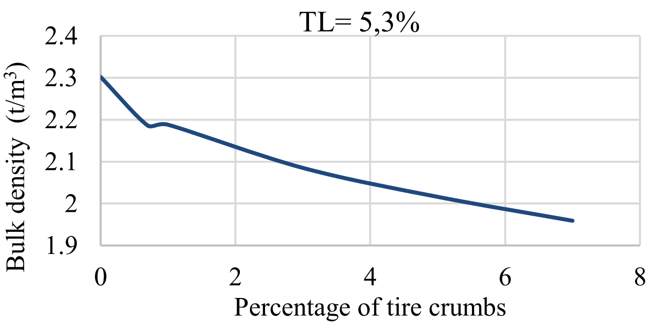



Fig. 6. Change in bulk density.

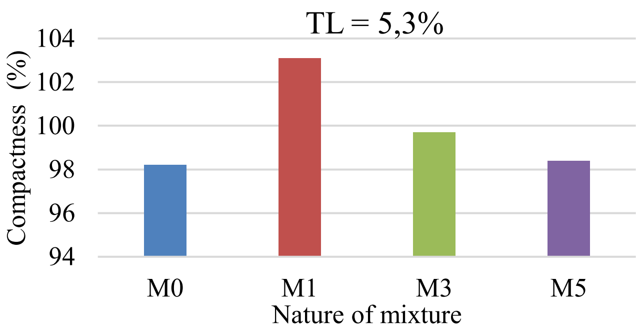



Fig. 7. compactness as a function of the tires content incorporated.

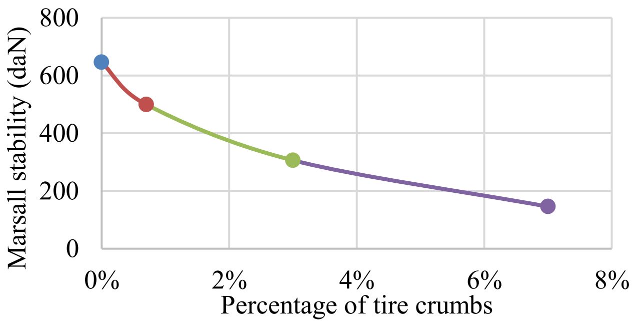



Fig. 8. Marshall stability according to the incorporated tires content. (TL = 5,3%).

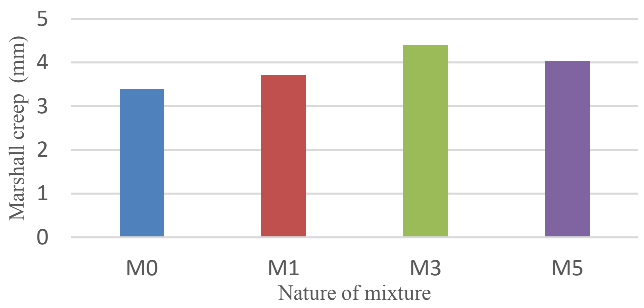



Fig. 9. Marshall creep according to the incorporated tires content.

## 5. Environmental study

The main objective of the environmental study is to assess the impacts of the bituminous concrete road containing waste tire crumbs for the long term and over its design life time. In order to minimize the negative impacts on the environment, it is important to investigate whether the construction and installation of regional bituminous concrete roads containing waste tire crumbs on either acid or basic soils should be recommended. In Tunisia we distinguish two different zones according to their soil pH (see Fig 12) Zone I and Zone II. The former, where the pH varies between 5 and 6, is the one with acidic soils and is located in the extreme North-West region. As for Zone II, where the soil pH varies between 7.5 to 9 or higher is called basic soils and it is in the rest of Tunisia).

To simulate acidic and basic soils, 100 ml solutions, adjusted to various pH, were prepared with 20 g of crushed bituminous concrete containing three different percentages of waste tire crumbs (0%; 0.7% &1%). Four different values of pH (Two acid solutions with pH= 1 & 5and two basic solutions with pH=11 & 12,5) were selected. The following four common environmental parameters were measured in order to assess the environmental impacts: Conductivity; Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (DCO). The results of the various tests are discussed in the following sections.

### 5.1. *Conductivity test.*

Conductivity measurement is a simple method to measure the ion concentration of the liquid phase of a substrate using the property of an aqueous solution to conduct electricity or heat in proportion to its concentration of the conductivity , or to resist the passage of the current in a manner inversely proportional to the ion concentration resistivity . Conductivity tests are conducted by many industries in various fields in order to determine the quality of their liquid wastes and evaluate the impact on the environment. The conductivity tests were conducted according the French Standard NF EN 27888, [53].

Table 7 summarizes the results of the conductivity tests for different % of waste tire crumbs placed in various solutions with different pH values. Fig. 10 shows the conductivity as a function of % of waste tire crumbs for pH = 5 & 11. Similar trends are obtained for pH = 1 & 12, 5

It can be observed that for a pH = 5 (acid solution), the conductivity decreases by 43% for a waste tire crumbs value of 1% compared to the initial condition of 0%. On the other hand, a considerable increase in conductivity of 220% is observed for a pH = 11 (basic solution). Based on conductivity tests it is obvious that acid soil conditions create less impact on the environment and are found to be more beneficial. For the 0,7% waste tire crumbs at a pH= 5, the conductivity decreased by 37%. This result is important since surface water quality is improved. Therefore, it is expected that the performance of the bituminous concrete with increasing waste tire crumbs in acid soil is enhanced as the conductivity is reduced.

### 5.2. *Measurement of TDS (NF EN 872),* [54].

The total dissolved solids (TDS) estimates the total residue remaining after evaporation of a sample of water that has been filtered with a filter with pore size of 1 mm. The combined content of all minerals and organic substances in a liquid in molecular, ionized or micro-granular (colloidal) biological suspension was measured. Table 8 summarizes the TDS results for various bituminous concrete mixtures for the different pH values. The TDS tests were conducted according the French Standard NF EN 872, [54].

Fig. 11 shows the impact of an acid or basic medium on a BC 0/14 bituminous concrete containing waste tires.

It can be observed from Fig. 11 that for a pH of 5, the TDS decreased by 45% for waste tire crumbs of 1%, while for a pH of 11, a significant increase in TDS of 240% is observed.

Congruent with the conductivity tests, the results of TDS tests confirm again the fact that the environmental impact of

Table 7
Variation of conductivity (mSiemens/cm) as a function of pH.

| Mixtures (% waste tires crumbs) | pH = 1 | pH = 5 | pH = 11 | pH = 12,5 |
|---|---|---|---|---|
| 0 | 30 | 25,7 | 2,56 | 11,84 |
| 0,7 | 29,4 | 16,3 | 5,38 | 14,78 |
| 1 | 24,7 | 14,6 | 8,16 | 15,53 |

Table 8
The variation of TDS (g/l) as a function of pH.

| Mixtures (% waste tires crumbs) | pH = 1 | pH = 5 | pH = 11 | pH = 12,5 |
|---|---|---|---|---|
| 0 | 17,79 | 15,09 | 1,3 | 6,54 |
| 0,7 | 17,83 | 9,15 | 2,83 | 8,27 |
| 1 | 14,9 | 8,25 | 4,4 | 8,76 |

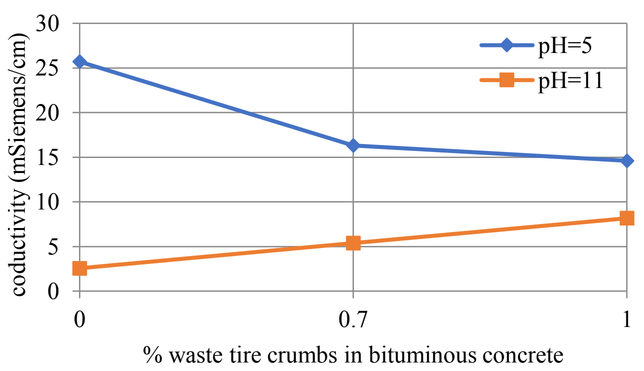



Fig. 10. Conductivity as a function of % of waste tires crumbs for pH = 5 & 11.

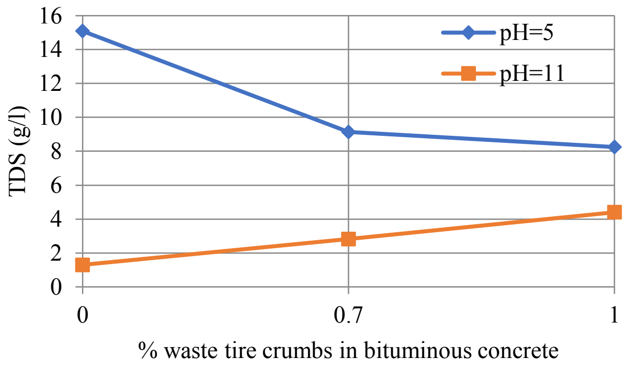
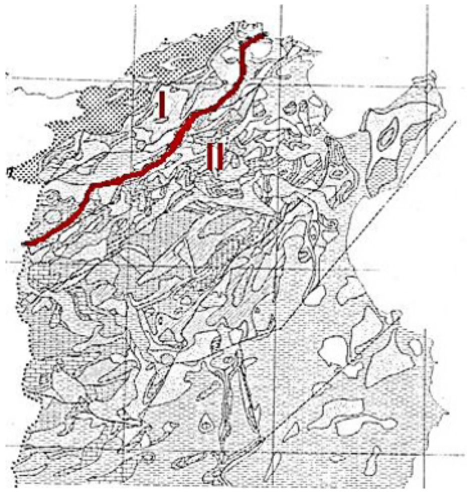



Fig. 11. Variation of the TDS as a function of % of waste of tires crumbs for pH = 5 & 11.




Soils of Tunisia - (Bulletin of Soils Division No. 5 1973)
Zone I: zone with an acid pH of 5 to 6
Zone II: zone with a basic pH of 7.5 to 9

Fig. 12. Map of the acid and basic zones of Tunisia.

embedded bituminous concrete with waste tire crumbs is less important in acidic than basic soils. So according to Tunisian soil classification discussed earlier, the BB0 / 14 with waste tire crumbs can be better used in zone I characterized by acidic soils rather than Zone II characterized by basic soils. Accordingly, the installation of the road creates less environmental impacts. Similarly to conductivity, the bituminous concrete with increasing waste tire crumbs performs better in acid soil rather than in basic soil since TDS is reduced.

### 5.3. *Biochemical oxygen demand.*

In order to characterize and evaluate the quality of polluted surface waters and wastewaters in terms of the concentration of organic compounds, the biochemical oxygen demand (BOD) tests are frequently used.

The BOD expressed in mg/l is an essential parameter that indicates the amount of oxygen ($O_2$) consumed by microorganisms in order to degrade the organic matter by biochemical processes. More specifically, a BOD5 is generally analyzed in the lab to indicate the amount of $O_2$ consumed during the period of 5 days in the dark at 20°C. Besides, the ultimate BOD (BODu) that corresponds to the maximum amount of $O_2$ consumed by microorganisms to degrade all biodegradable organic matter can be determined by the BOD curve. The BOD tests were conducted according to the French Standard NF EN 1899-1, [55]. Fig. 13 shows the BOD experimental results obtained for the 0%, 0,7% and 1% of waste tire crumbs.

The tests were conducted at pH level close to neutrality (pH = 7 to 7,5) in order to simulate the natural degradation of organic materials in rivers and lakes. Over the life time design (usually 15 to 20 years) of bituminous concrete roads, the major part of the road will disintegrate into small pieces and will find their ways into rivers, lakes and estuaries. The waste tire crumbs released into the hydraulic environment will lead to biological degradation measured by BOD.

The curves in Fig. 13 show that the amount of organic matter in the form of BOD increased by about 60% for mixtures with 0.7% and 1% of waste tire crumbs compared to that present in the control mixture of 0% waste tire crumbs. This increase of BOD is due to the presence of waste tire crumbs in the bituminous concrete. Similar conclusions can be obtained from comparing the results of BOD5. As shown in Fig 13, no major differences were found between samples containing 0,7% and 1% waste tire crumbs. These results show that the organic matter will be degraded over the short term and are not found to be toxic to biological activity. In short and in terms of releasing biodegradable matter into the surrounding environment, the performance of bituminous concrete with waste tire crumbs was found to be similar for the samples 0,7% and 1% waste tires crumbs.

### 5.4. *Chemical oxygen demand.*

Similar to BOD, the chemical oxygen demand (COD) corresponds to the amount of oxygen necessary for the complete oxidation of the organic material in water and wastewater. The oxidation is carried out in a sulphuric acid solution using potassium dichromate (strong chemical oxidant) heated at a temperature of 150°C during 2 hours. The COD measures the O2 required to chemically oxidizing total organic matter present in solution including the non-biodegradable organic matter by microorganisms. The COD tests were conducted according to the French Standard NF T90-101, [56]. Fig. 14 shows the COD experimental results obtained for the 0%, 0,7% and 1% of waste of tires crumbs. Fig. 14 shows that as the % of the waste crumb tires increased the COD decreased

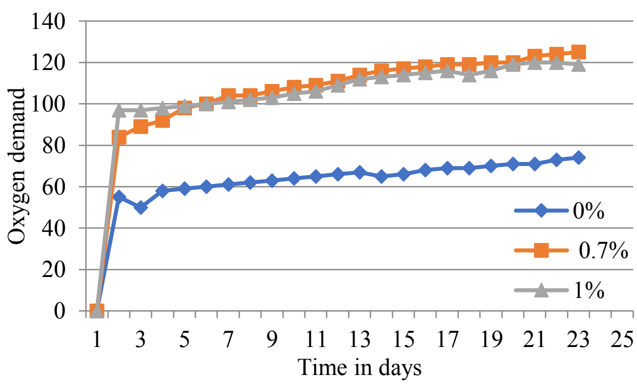



Fig. 13. Experimental BOD curves for the three % of waste tires crumbs.

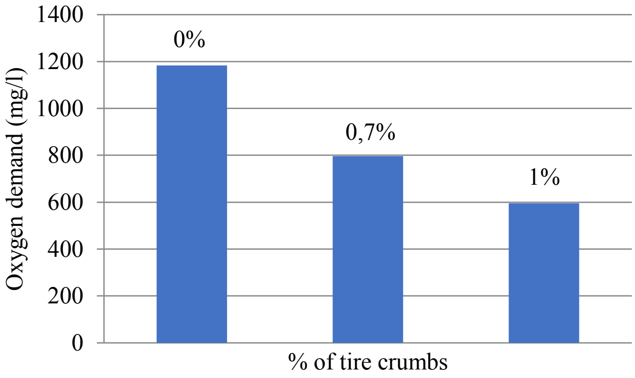



Fig. 14. Experimental COD results for the three % of waste tires crumbs.

by as much as 50%. This can be considered an environmental benefit since it is due, probably, to the substitution of non-biodegradable matter present in the bituminous concrete with the waste of tires crumbs. Therefore and contrary to BOD, the performance of bituminous concrete in terms of releasing biodegradable and non biodegradable matter (i.e., COD) into the adjacent environment was found to decrease with increasing percentage of waste tire crumbs.

Table 9 shows comparisons of the ratios of BOD to COD. Since COD values are in all cases more that 2 to 3 times higher than the BOD, the organic matter present in the samples are considered difficult to biodegrade and a biological treatment process is difficult to apply. This can be considered a drawback since some of the organic matter released by the bituminous concrete will remain in the aquatic environments for a longer duration before being degraded by microorganisms. However, on the positive side and as previously demonstrated by the BOD test, the organic materials contained in the waste tire crumbs released into the environment is not toxic to microorganisms found naturally in the aquatic environment but it may take some time to be degraded naturally.

## 6. Conclusions

This work deals with the study of a new formulation of a bituminous concrete from crumbs of used tires reused by partial substitution of crushed sand and gravel and aims to highlight the impact of this incorporation on the compactness of material, resistance to water, compressive strength, creep and stability Marshall.

A global approach of the comparison between the characteristics of the different bituminous mixtures according to the crumb content of the tires and the contents of the binder led us to the conclusions below:

1. The lower limit required for a BC 0/14 of the compressive strength R is 7MPa. This value is reached only for mixing with 0.7% tires crumbs for TL = 5.3% and for a porosity of 2%.
2. The modification of bituminous mixtures using tires crumbs improves the water sensitivity ratio (r/R), it is well noted that for all the series with TL = 5.3%, are close to 0.75, which corresponds to the minimum value required by the CCTP for a BC 0/14.

Table 9
Ratios of BOD5/COD and BODu/COD.

| Mixtures (% waste tires crumbs) | $BOD_5$/COD | $BOD_u$/COD |
|---|---|---|
| 0 | 0,05 | 0,07 |
| 0.7% | 0,12 | 0,18 |
| 1% | 0,17 | 0,24 |

3. The incorporation of tires improves compactness for all mixtures.
4. The bulk density of the BC 0/14 with the addition of tires crumbs decreases linearly
5. For the M5 mixture with 0.7% of the tires, the Marshall stability has decreased.
6. An increase in creep of the order of 15% was observed for the mixture M5, concerning the reference mixture.

The M5 blend with 0.7 %, 0.5/3 mm tire crumbs, 47% crushed sand 0/4, 15.3 % gravel 4/8, 37 % gravel 8/14 and a binder content of 5.3 % represents the optimal characteristics sought in this work.

The impact of the acidic solution (pH = 5) resulted in a decrease of the conductivity by 43% for a waste of tires crumbs of 1%, but a considerable increase of 220% is observed in conductivity for a base solution of pH = 11. Similar values were obtained for TDS which decreased for an acid solution by 45% for waste of tires crumbs of 1%, while for a pH of 11, a significant increase of 240% is observed. Consequently, it is observed that the performance of the bituminous concrete with increasing waste tire crumbs in acid soil is enhanced while the conductivity is reduced. Similar trends were observed for TDS.

Tunisia soils are subdivided into two zones, acidic and basic, Zone I having acid soils with 5 < pH < 6 and zone II having basic soils with 7.5 < pH < 9. According to the total dissolved solids measurements, it is concluded that the environmental impact of bituminous concrete incorporating waste of tires crumbs is less significant in an acidic than basic environments, favoring the use of BC 0/14 with waste of tires crumbs in zone I (acidic soils).

This study showed that as the % of waste tires crumbs increased, the COD decreased by as much as 50%. This can be considered an environmental benefit due to the substitution of non-biodegradable matter present in the bituminous concrete with the waste of tires crumbs. In addition, it was observed that the values of COD are in all cases more that 2 to 3 times higher than the BOD and this proves that the organic matter present in the samples are considered difficult to biodegrade and a biological treatment process is difficult to apply. As far as the release of biodegradable matter into the surrounding environment is concerned, the performance of bituminous concrete with waste tire crumbs was found to be similar for the samples 0,7% and 1% waste tires crumbs. On the other hand, and contrary to BOD, the performance of bituminous concrete in terms of releasing biodegradable and non biodegradable matter (i.e., COD) into the adjacent environment was found to decrease with increasing percentage of waste tire crumbs.

Future research requires further testing to determine the resistance to permanent deformations in order to avoid the risk of rutting at high operating temperatures by the LCPC rutting test, resistance to cracking at low temperatures and fatigue testing to predict pavement durability.

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