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Comparative numerical and experimental studies of the tensile strengths of concrete incorporating recycled and natural aggregates

Arba Achyle Télesphore OUEDRAOGO [1,*], Etienne MALBILA [1,2], Nicolas KAGAMBEGA [1,3] and David Y. K TOGUYENI [4,5]

[1] *Higher School of Engineering (ESI), University of Fada N'Gourma (UFDG), Fada-N'Gourma, Burkina Faso.*
[2] *Renewable Thermal Energy Laboratory (LETRE), Joseph KI ZERBO University, Ouagadougou, Burkina Faso.*
[3] *Geosciences and Environment Laboratory (LaGE), Joseph KI ZERBO University, Ouagadougou, Burkina Faso.*
[4] *Environmental Physics and Chemistry Laboratory (LPCE), Joseph KI ZERBO University, Ouagadougou, Burkina Faso.*
[5] *Polytechnic School of Ouagadougou (EPO), Ouagadougou, Burkina Faso.*

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Abstract

The aim of this study is to carry out a comparative numerical and experimental analysis of the tensile strengths of concrete. To do this, a physical and mechanical characterization of the aggregates was carried out, followed by the formulation of current concretes. Tensile strength characterization tests and a theoretical numerical study according to BAEL 91 revised 99 and Eurocode 2 of the concrete samples were carried out. The analysis of tensile strengths shows that at 7 days of age the average tensile strengths calculated according to Eurocode 2 are higher than those experimental and BAEL 91 revised 99. At 28 days of age, the experimental results are higher than the theoretical results obtained, except for the average tensile strengths of BR2 (2.25 MPa) and BC1 (2.23 MPa) of Eurocode 2, which are slightly higher than those obtained experimentally (BR2=2.08 MPa ; BC1=2.09 MPa). Furthermore, the relationship established between the theoretical and experimental results shows at 7 days of age that the average tensile strengths according to BAEL 91 revised 99 are closer to those experimental with respectively a correlation coefficient and the standard error equal to 0.502 and 0.1687. At 28 days of age those of Eurocode 2 are closer to the experimental values with respectively a correlation coefficient and the standard error equal to 0.9206 and 0.0813. From these analyses, it can be seen that Eurocode 2 provides a better prediction of the mechanical tensile behaviour of concrete based on recycled and/or natural aggregates.

Keywords: Numerical analysis; Experimentation; Tensile strength; Recycled aggregates; Natural aggregates.

1. Introduction

The behavior of a construction is assessed on the scale of a part of the structure and/or the entire structure. This behavior is intrinsically linked to the nature and characteristics of the material used. Nowadays, concrete remains the most used material in construction due to its multiple advantages compared to other traditional construction materials [1]. Scientific research on concrete makes it possible to understand the complex mechanical behavior of this material both in the fresh and hardened state, and to improve its implementation conditions as well as its mechanical performance and its durability [1].

Thus, compressive and tensile strength are two important parameters used for the design of concrete elements [2]. Particularly, tensile strength is an essential parameter, not only to intrinsically characterize the material concrete [3], wood [4, 5], steel [6], earthen bricks [7, 8, 9] etc., but also to assess the safety of structures [3], based on these materials.

* Corresponding author: Arba Achyle Télesphore OUEDRAOGO.

It can be estimated by three methods, namely the direct tensile test [10], the Brazilian test (or splitting tensile test) [11], and the flexural test [12]. It is widely known that the split cylinder test is simpler and provides reliable data under uniform stress [2, 13].

However, from an experimental and theoretical point of view this is not always obvious, in particular for concretes incorporating aggregates from demolition. To do this, a numerical study is necessary in order to assess the results from splitting tensile tests on concrete incorporating natural and recycled aggregates. This numerical study takes into account the formulas proposed by BAEL 91 revised 99 [14] and Eurocode 2 [15], as part of the evaluation of the tensile strength of concrete.

2. Materials and Methods

The study carried out is intended to be numerical and experimental for a comparison of the tensile behavior of concrete. The framework of the study is as shown in figure 1 below:

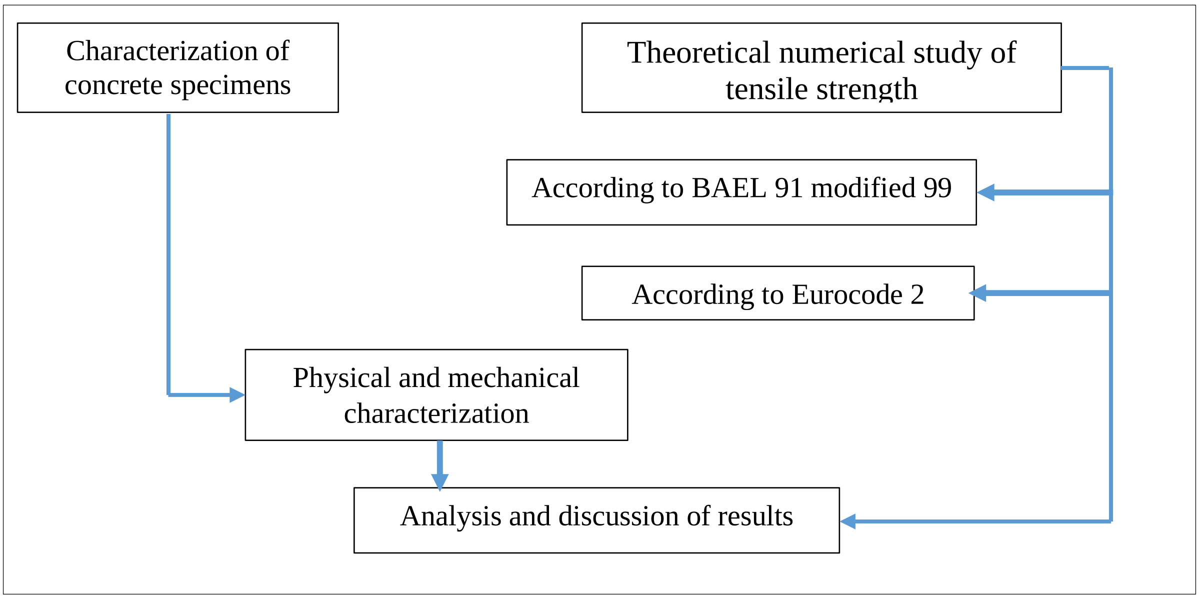

Figure 1 Study framework

2.1. Raw Materials

2.1.1. Cement

In this study, the cement used for the formulation of common concrete is standard cement from CIMBURKINA. It is CEM II 42.5 R class cement, with a specific mass of 3.10 g/cm^3 manufactured in the Ouagadougou industrial zone in Burkina Faso in accordance with the NBF 02-013 standard.

2.1.2. Aggregates

The aggregates used in this study, are of four types. These are :

- Natural sand 0/5 (rolled) from Manga, taken from the Donsin airport site ;
- Recycled sand 0/2 (rolled) from the crushing of concrete blocks extracted in Kamboinsin ;
- 16/25 natural aggregates (crushed granite) recovered from the Yiimdi quarry, taken from the Donsin airport site;
- 16/25 recycled aggregates (crushed granite) from the fragmentation of structural demolition concrete blocks (relatively clean), from the slab of the Dapoya Shell station being repaired, and from the northern interchange bridge.

Figure 2 Aggregate sample **[16]**

The natural and recycled aggregates particle size curves are shown in figure 3 below :

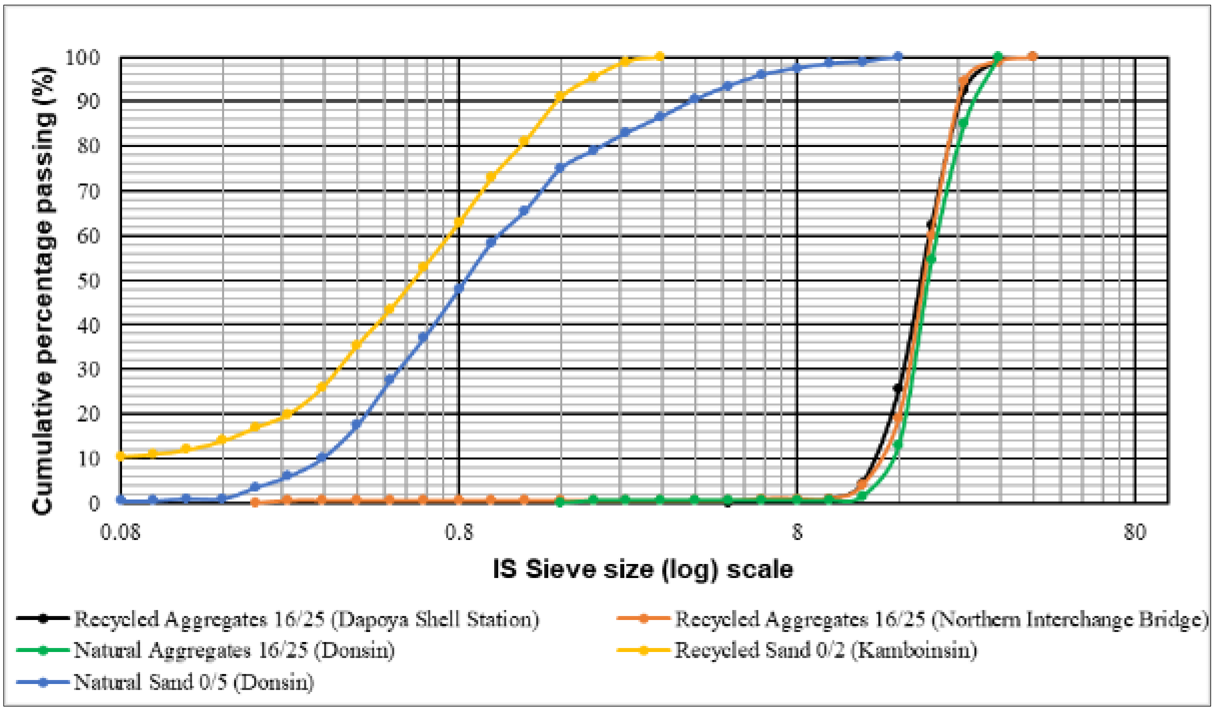

Figure 3 Particle size distribution of natural and recycled aggregates. **[16]**

In figure 3, we notice that the recycled sand from Kamboinsin (0/2mm) is finer compared to the natural sand from Donsin (0/5mm) which is coarse. This obtained granular class (0/2 mm) can be explained by the crushing energy not necessarily controlled (manual crushing) and the sifting carried out during the recycled sand processing. Also, there is an important quantity of the particle size 0.2/5 mm and 1.6/5 mm respective in the recycled aggregates from northern interchange and natural aggregates from Donsin. The physico-mechanical characteristics of these aggregates are summarized in table 1 below.

Table 1 Physico-mechanical characteristics of aggregates **[16]**

Characteristics	**Units**	**Aggregate types**					**Specification for hydraulic concrete** [17, 18]
		Sand		crushed granites			
		Natural Sand (Donsin)	Recycled Sand (Kamboinsin)	Naturel crushed (Donsin)	Recycled crushed (Northern Interchange Bridge)	Recycled crushed (Dapoya Shell Station)	
Granular class (d/D)	mm	0/5	0/2	16/25	16/25	16/25	
Fineness modulus (MF)		2.27	3.1				1.8 ≤ MF ≤ 3.2
Flattening coefficient (A)	%			16.47	7.63	9.87	Vss(A) ≤20 et Vss(C) ≤40
% fines < 0.08mm	%	0.5	10.5				Vss(A) ≤12 et Vss(C) ≤18
Apparent volumetric mass	g/cm^3	1.47	1.35	1.45	1.46	1.48	ρ_{ap} > 1200 kg/m^3
Absolute density	g/cm^3	2.63	2.66	2.65	2.65	2.65	2200kg/m^3 < ρ_a < 3000 kg/m^3
Actual density after oven drying	g/cm^3			2.63	2.6	2.61	2200 kg/m^3 < ρ_{rd} < 3000 kg/m^3
Actual saturated dry surface density	g/cm^3			2.64	2.61	2.62	2200 kg/m^3 < ρ_{rsd} < 3000 kg/m^3
Water absorption coefficient	%			0.22	0.93	0.57	Vss ≤ 2.5 et Vss(C) ≤ 6
Visual Equivalent of sand	%	89.3	72				ESV > 65%
Equivalent of sand on piston	%	85	66				ESP > 60
Superficial cleanliness	%			0.51	0.56	0.54	Vss ≤ 1.5 ou 3
Los Angeles (LA) Coefficient	%			28	19	18	LA ≤ 30

2.1.3. Mixing Water

The National Lab of Building and Public Works (LNBTP) is supplied with water by the National Office of Water and Sanitation (ONEA) in accordance to standard NF EN 1008 [19]. This water taken from tap for concrete mixing is free of impurities and presents the characteristics of the drinking water.

2.2. Mixing Formulation and Preparation of concrete specimens

The Dreux-Gorisse method [20] is the one used in this study for the mixing formulation. Thus five (05) current concrete formulations BR1, BR2, BN, BC1 and BC2 were produced, with different granular compositions illustrated in table 2. For each type of concrete, the mixing proportions were determined and defined in table 3, taking into account the main physical and mechanical characteristics of the aggregates illustrated in table 1.

The specimens were made in accordance with standard NF EN 12390-2 [21], with the equipment available to the LNBTP Lab.

Table 2 Description and granular compositions of the different studied concretes **[16]**

Concrete Item	Description	Recycled sand from Kamboinsin	Natural Sand from Donsin	Natural granite aggregate from Donsin	Recycled granite aggregate from Dapoya	Recycled aggregate form Northern interchange
		0/2	0/5	16/25	16/25	16/25
BR1	*Recycled aggregate (RA) concrete 1*	+			+	
BR2	*Recycled aggregate (RA) concret 2*	+				+
BN	*Reference concrete (NA base concrete)*		+	+		
BC1	*Combined aggregate (CA) concrete 1*		+		+	+
BC2	*Combined aggregate (CA) concrete 1*	+		+		

Table 3 Components dosage per 1m^3 of concrete **[16]**

Concrete components	Unit	BR1	BR2	BN	BC1	BC2
Recycled granite aggregate 16/25	kg	1138.18	1138.18		1007.56	
Natural granite aggregate 16/25	kg			985.17		1133.83
Recycled Sand 0/2	kg	730.44	730.44			730.44
Natural Sand 0/5	kg			870.35	851.83	
Cement CEM II 42,5 R	kg	350	350	350	350	350
Mixing Water	kg	190.22	190.22	190.22	190.22	190.22
Ratio C/W		1.84	1.84	1.84	1.84	1.84

2.3. Characterization of concrete specimens

2.3.1. Physical characterization tests

Characterization of aggregates

The aggregates used in the concrete manufacture must have characteristics that comply with the standards in force, in particular the granularity [22], the shape of the aggregate [23] the densities and water absorption [24, 25] the cleanliness [26, 27] and the hardness [28]. To obtain a quality concrete, it is necessary to use components in quantities naturally or after recycling and/or treatment, as discussed by [29] for the aggregates.

Workability of concrete

The test carried out on fresh concrete, concerns its workability by the slump measuring with the Abrams cone, in accordance with the standard NF EN 12350-2 [30].

Bulk density (ρ_{ap})

By weighing the masses of the specimens subjected to the tensile tests, the apparent density is obtained by application of the following formula 1 :

$$\boldsymbol{\rho_{ap}} = \frac{M}{V} \quad (kg/m^3) \qquad (1)$$

With :

ρ_{ap} : the apparent density of the hardened concrete at "D " days (in kg/m^3);

M : the mass of the specimen of hardened concrete at "D " days (in kg) ;

V : the volume of the specimen (in m^3).

The weighing of the specimens concerned six specimens of each formulated concrete, at the 7^{th} and 28^{th} days of hardening age.

2.3.2. Tensile strength characterization tests (Ft)

The tensile strength is determined by a splitting tensile test on cylindrical specimens (16 cm x 32 cm and 15 cm x 30 cm), in accordance with standard NF EN 12390-6 [11]. The test consists to crush a concrete cylinder following two opposite generatrices between the plates of a press [18]. It is determined on the 7^{th} and 28^{th} days of hardening age, on three (03) samples of each type of common concrete (i.e. 15 test specimens in total). The tensile strength values (F_t) sont are obtained by applying the following formula 2 :

$$\boldsymbol{F_{tj} = 2 \times \frac{P}{\pi . D . L}} \qquad (2)$$

With :

- *F_{tj} : tensile stress at "D" days of age (in MPa) ;*
- *P : value of the breaking load (in N); ;*
- *D and L : diameter and length of the cylinder (in mm).*

2.3.3. Predictive theoretical calculation of tensile strength

For a better assessment of the tensile strength of concrete, a numerical study will be carried out in application of the BAEL 91 modified 99 [14] and Eurocode 2 [15] standards, in using the following expressions :

$$\boldsymbol{F_{t28} = 0,6 + 0,06 \times f_{cj}} \quad \textbf{(BAEL 91 revised 99, article : A.2.1, 12)} \qquad (3)$$

And

$$\boldsymbol{F_{ctm} = 0,3 \times f_{ck}^{2/3}} \quad \textbf{(Eurocode 2, chapter 1 : 1.2.1)} \qquad (4)$$

With :

F_{t28} and F_{ctm} : the average tensile strengths at 28 days (in MPa);

F_{ck} and F_{cj} : : the average compressive strengths at 28 days (in MPa);

3. Results

3.1. Average tensile strength at 7 days of age

The results of theoretical calculations of the average tensile strength at 7 days of age, compared to tensile crushing by splitting of current concretes and the different established relationships are represented in figures 4, 5, 6, 7 and 8 below.

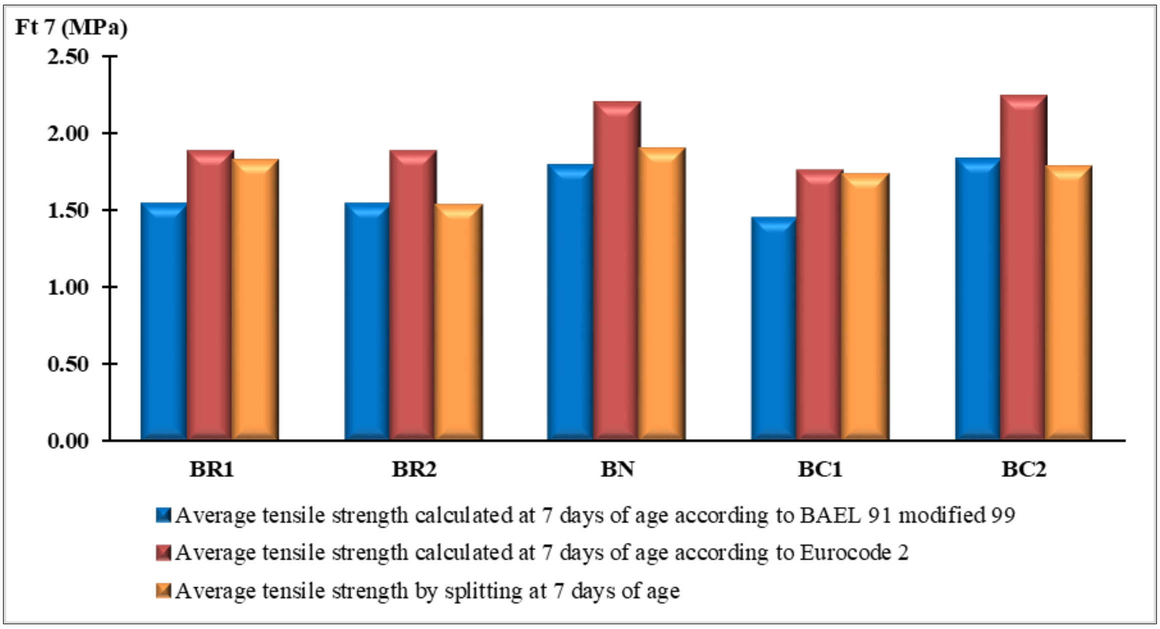

Figure 4 Average tensile strengths at 7 days of age

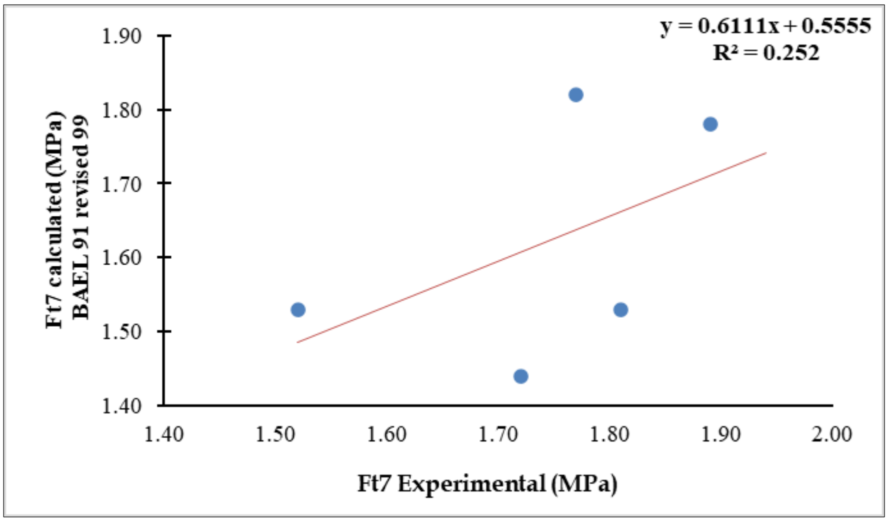

Figure 5 Relationship between the average tensile strength at 7 days of age calculated according to BAEL 91 revised 99 and experimentally measured

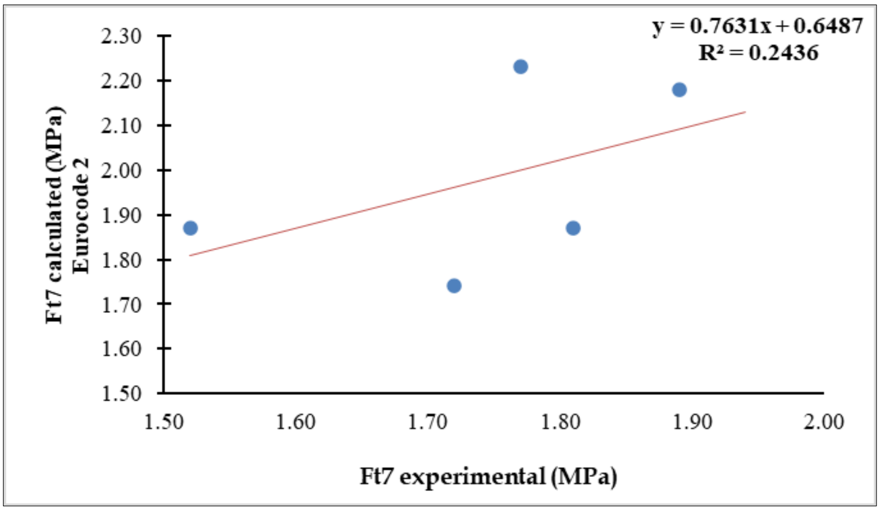

Figure 6 Relationship between the average tensile strength at 7 days of age calculated according to Eurocode 2 and experimentally measured

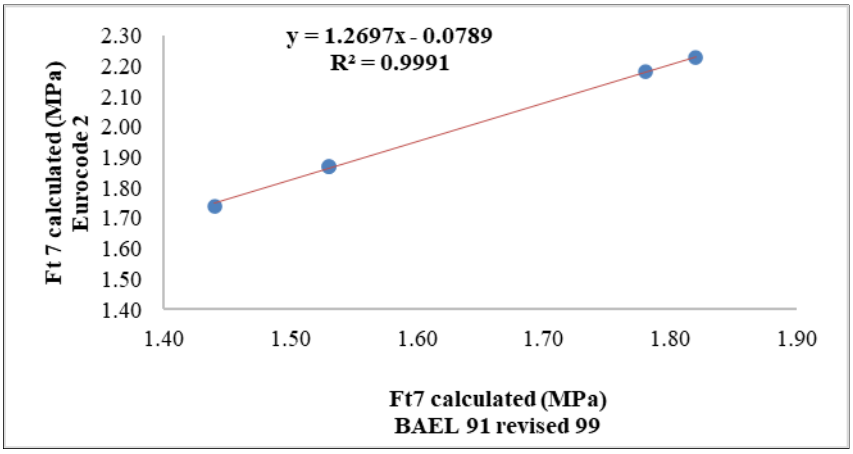

Figure 7 Relationship between the average tensile strength at 7 days of age calculated according to BAEL 91 revised 99 and Eurocode 2

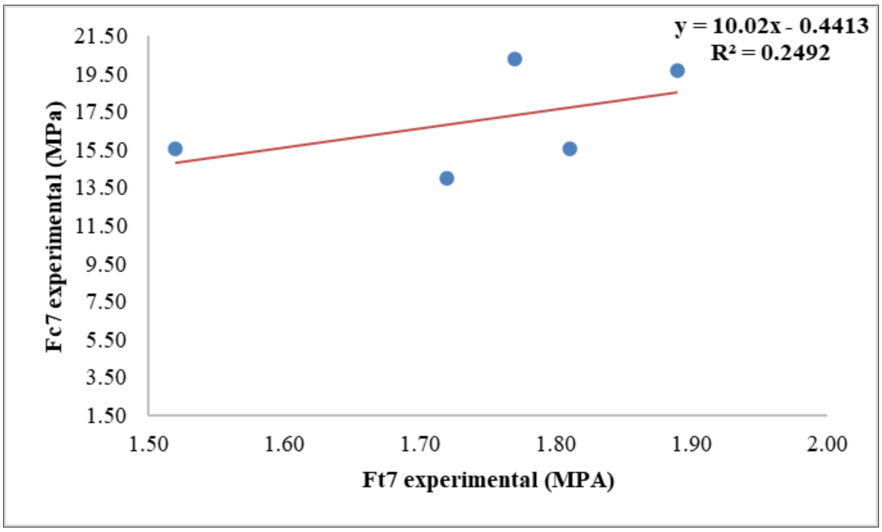

Figure 8 Relationship between average tensile strength and compressive strength experimentally measured at 7 days of age

Figure 4 shows that the average tensile strengths of calculation according to Eurocode 2 [15], are higher than those of BAEL 91 revised 99 [14] and splitting tensile [11] at the 7th day of age.

The average tensile strengths obtained by applying equation 3 of BAEL 91 revised 99 (figure 4) [14], are lower than those of the splitting tensile tests except for the F_{t7} values of concretes BR2 (1.53 MPa) and BC2 (1.82 MPa) which are slightly higher than those of splitting tensile (BR2 = 1.52 MPa ; BC2 = 1.77 MPa). Thus a maximum difference of 16.28% at the level of BC1 and a minimum of 0.89% at the level of BR2 are noted. In addition, the comparison of the calculation results of BAEL 91 revised 99 [14], with those experimental (splitting tensile test) at 7 days of age (figure 5), show that the Pearson correlation coefficient **r** and the standard error are 0.502 and 0.1687 respectively. This shows in fact a fairly suitable concordance between the average tensile measured strengths and those calculated.

According to equation 4 of Eurocode 2 [15], the average tensile strengths of calculations obtained (figure 4) are higher than those of the splitting tensile tests. Thus, a maximum difference of 20.72% at BC2 and a minimum of 1.30% at BC1 are observed. Furthermore, the calculation results of Eurocode 2 [15], compared to those experimental (splitting tensile test) at 7 days of age (figure 6), show that the Pearson correlation coefficient **r** and the standard error are 0.493 and 0.2155 respectively. This shows in fact, a fairly suitable relationship between the average tensile measured strengths and those calculated.

Also, the application of equation 3 of BAEL 91 modified 99 [14] and 4 of Eurocode 2 [15], show that at 7 days of age the average tensile strengths obtained according to Eurocode 2 are higher than those of BAEL 91 modified 99 (figure 4) [14]. Thus, a maximum difference of 18.57% at BC2 and a minimum of 17.37% at BC1 are noted. In addition, the calculation results of BAEL 91 revised 99 [14], compared to those of Eurocode [15] at 7 days of age (figure 7), show that the Pearson correlation coefficient **r** and the error type are 0.9995 and 0.0075 respectively. This indeed shows, a suitable relationship of the average tensile calculated strengths according to BAEL 91 revised 99 [14] with those of Eurocode 2 [15].

The relationship established between the experimental results of traction and those of compression at 7 days of age (figure 8), show a Pearson correlation coefficient **r** of 0.4992 and a standard error of 2.7880. This indeed shows, a fairly suitable concordance between the average tensile strengths with those of compression from tests.

Thus, the forecast estimates of the average tensile strengths at seven (07) days of age, by application of equation 3 of BAEL 91 revised 99 [14], make it possible to obtain average tensile strengths close to those experimental , compared to those of equation 4 of Eurocode 2 [15].

3.2. Average tensile strength at 28 days of age

The results of the predictive estimates of the average tensile strength at 28 days of age, compared with the splitting tensile crushes of current concretes and the various established relationships are shown in figures 9, 10, 11, 12 and 13 below.

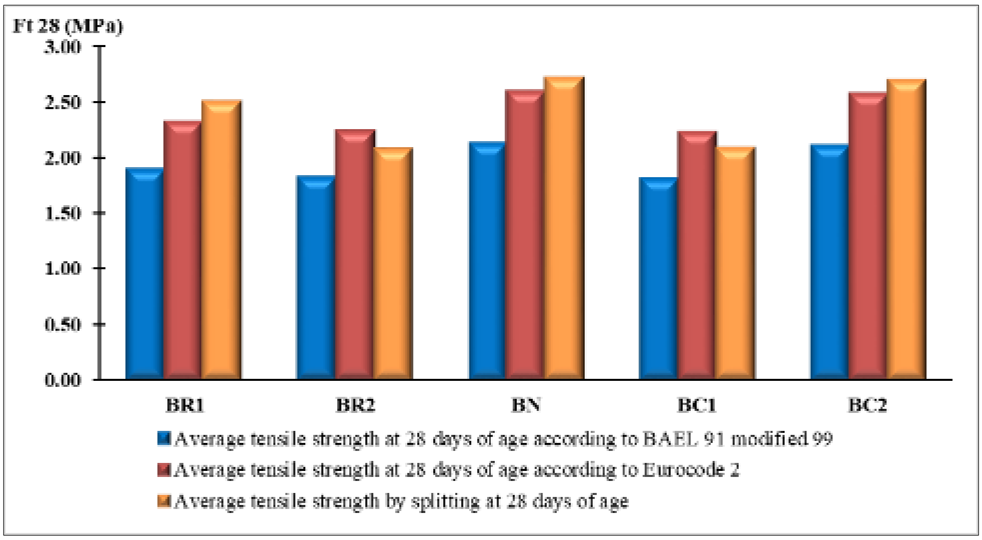

Figure 9 Average tensile strength at 28 days of age

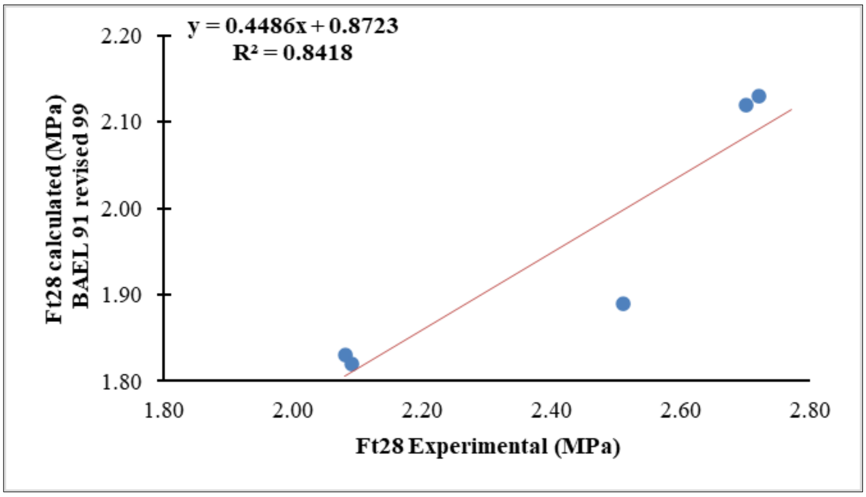

Figure 10 Relationship between the average tensile strength at 28 days of age calculated according to BAEL 91 revised 99 and experimentally measured

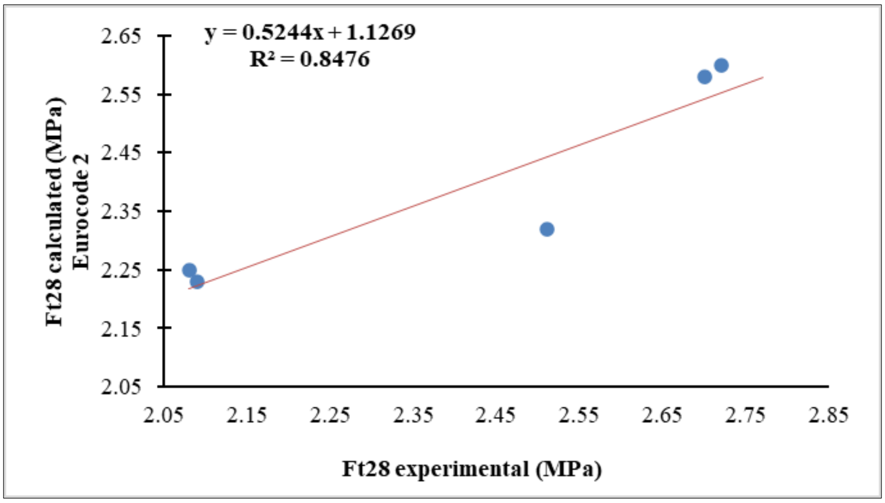

Figure 11 Relationship between the average tensile strength at 28 days of age calculated according to Eurocode 2 and experimentally measured

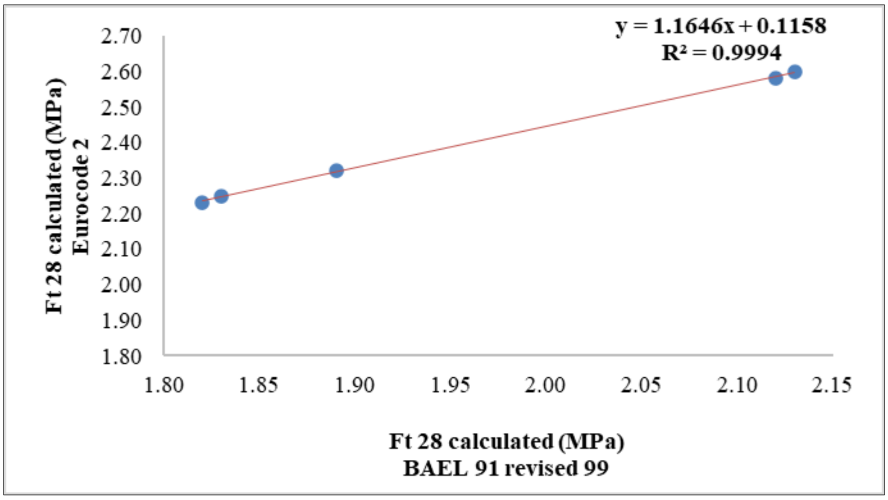

Figure 12 Relationship between the average tensile strength at 28 days of age calculated according to BAEL 91 revised 99 and Eurocode 2

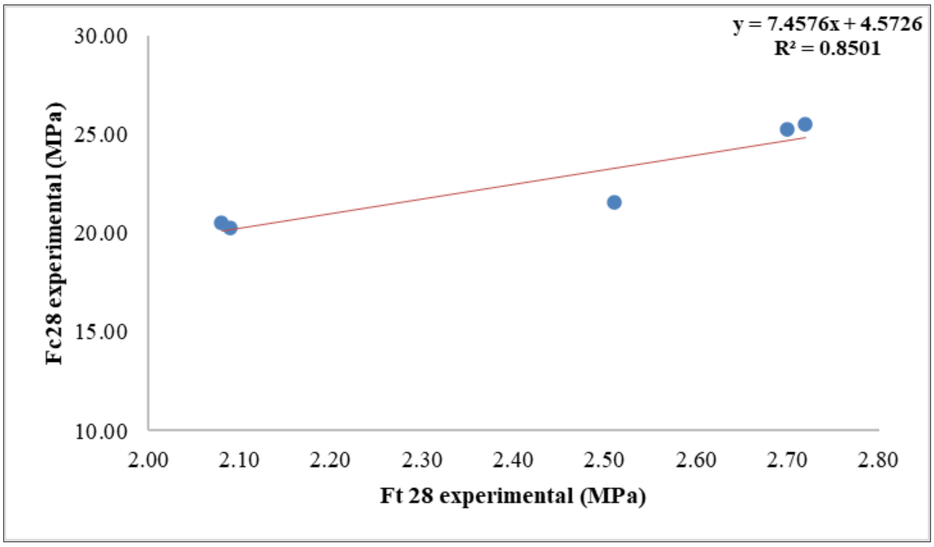

Figure 13 Relationship between average tensile strength and compressive strength experimentally measured at 28 days of age

Figure 9 shows that the average tensile strengths at 28 days of age, estimated according to BAEL 91 revised 99 [14], are slightly lower than those tested. Thus a maximum difference of 24.58% at BR1 and a minimum of 12.02% at BR2 are noted. In addition, the comparison of the calculation results of the BAEL 91 Revised 99 [14], with the experimental results (splitting tensile test) at 28 days of age (figure 10), shows that the Pearson correlation coefficient **r** and the standard error are 0.9174 and 0.0711 respectively. This indeed shows, an acceptable concordance between the average tensile measured strengths and those calculated.

For calculations carried out according to Eurocode 2 [15], the results obtained (figure 9) are also slightly lower than those obtained experimentally, except for the F_{ctm} values of concretes BR2 (2.25 MPa) and BC1 (2.23 MPa) which are slightly higher than the tensile splitting results (BR2 = 2,08 MPa ; BC1=2,09 MPa). Thus a maximum difference of 7.44% at BR1 and a minimum of 4.37% at BC2 are observed. Furthermore, the calculation results of Eurocode 2 [15], compared with the experimental results (splitting tensile test) at 28 days of age (figure 11), show that the Pearson correlation coefficient **r** and the standard error are 0.9206 and 0.0813 respectively. This indeed shows, a suitable relationship between the average tensile measured strengths and those calculated.

Also, the application of equation 3 of BAEL 91 modified 99 [14] and 4 of Eurocode 2 [15], show that at 28 days of age the average tensile obtained strengths according to Eurocode 2 [15] are higher than those of BAEL 91 modified 99 (figure 9) [14]. Thus a maximum difference of 18.57% at BC1 and a minimum of 18.05% at BN are noted. In addition, the comparison of the calculation results of BAEL 91 revised 99 [14], with those of Eurocode 2 [15] at 28 days of age (figure 12), show that the Pearson correlation coefficient **r** and the standard error are 0.9997 and 0.0052 respectively. This shows in fact, an acceptable concordance of the average tensile calculated strengths according to BAEL 91 revised 99 with those of Eurocode 2.

The relationship established between the experimental tensile results and those of compression at 7 days of age (figure 13), show a Pearson correlation coefficient **r** of 0.9220 and a standard error of 1.1445. This indeed shows, a suitable concordance of the average tensile strengths with those of compression from tests.

Thus, the calculation obtained results according to BAEL 91 revised 99 [14] and Eurocode 2 [15], show that those of Eurocode 2 give average tensile strengths at 28 days of age close to those of crushing by splitting. Despite the differences observed, the calculated values and those deduced from the tests are of the same order of magnitude. They are used in reinforced concrete, particularly in simple tension, shear force and compound bending calculations.

4. Discussion

In previous studies, it has been noted that the splitting tensile strength $f_{ctm,sp}$ of natural aggregate concrete is often deduced from f_{cm}. To do this, several authors have sought to correlate the splitting tensile strength with the compressive strength [31, 32, 33, 34, 35, 36]. All the proposed models can be written in the form $f_{ctm,sp} = \eta_1 \times f_{cm}^{\eta_2}$, with the exception of the Eurocode 2 model ($f_{ctm,sp} = 0.30 \times f_{ck}^{\frac{2}{3}}$) which takes into account the characteristic compressive strength f_{ck} and not the average compressive strength, f_{cm}. The results show that the empirical proposed models do not adequately predict the splitting tensile strength of concrete made from recycled aggregates. Thus, the estimation of the average splitting tensile strength of concretes incorporating recycled aggregates in the present study is more or less satisfactory. Indeed, the application of equations 3 of BAEL 91 revised 99 [14] and 4 of Eurocode 2 [15]] respectively, makes it possible to obtain acceptable results at 7 and 28 days of age, which are close to those experimental.

The tensile behavior of recycled aggregate concrete studied by [37], shows that Pearson's **r** and the standard error of the obtained estimate were equal to 0.766 and 0.39, for the relationship between tensile measured and calculated strengths using the formulas of Eurocode 2 and the results obtained by [34]. In the same sense as the present study, the relationship between the average tensile measured strength and that calculated according to Eurocode 2, shows at the 28th day of age a Pearson correlation coefficient **r** and the standard error which are respectively 0.9206 and 0.0813. This indeed shows, a suitable relationship between the average tensile measured strengths and those calculated.

Furthermore, the analyzes carried out by [37, 38, 39], show that the recycling rate has no effect on the relationship between $f_{ctm,sp}$ and f_{cm}. Compared with our results obtained on calculations according to BAEL 91 revised 99 [14] and Eurocode 2 [15] for BC1 and BC2, we note that the substitution rate has an effect on the relationship between f_{ctm} , f_{cm} *and* f_{ck}. The observation is made on the calculation obtained results, which show that the tensile strengths of BC2 (which contains 39% recycled sand) are higher compared to BC1 (which contains 54% recycled aggregate). Thus, the aggregate type and the mix ratio are the factors that can support this difference in the tensile estimated strength of BC2 (BAEL 91 revised 99 = 2.12 MPa ; Eurocode 2 = 2.58 MPa) and BC1 (BAEL 91 revised 99 = 1.82 MPa ; Eurocode 2 = 2.23 MPa) at 28th day of age.

5. Conclusion

This analysis focused on the comparative numerical and experimental study of the tensile strengths of concretes incorporating recycled and natural aggregates. The following results emerge from this analysis :

- At 7 days of age, the average tensile strengths of calculation obtained according to BAEL 91 revised 99 and Eurocode 2, show that those of BAEL 91 revised 99 are close to those of experimental tests compared to those of Eurocode 2 ;
- At 28 days of age, the average tensile strengths of calculation obtained according to BAEL 91 revised 99 and Eurocode 2, show that those of Eurocode 2 are close to those of experimental tests compared to those of BAEL 91 revised 99 ;
- Comparison of the average tensile strengths obtained from the calculations shows that those of Eurocode 2 are higher than those of BAEL 91 modified 99, at 7 and 28 days of age with a determination coefficient of 0.9991 and 0.9994 respectively ;
- The theoretical formulas allow a suitable prediction of the experimental average strengths at 28 days of age with a determination coefficient of 0.8418 (for the relationship between the average calculated strengths according to BAEL 91 modified 99 and those experimentally measured) and 0.8476 (for the relationship between the average calculated strengths according to Eurocode 2 and those experimentally measured) compared to that at 7 days of age which are 0.252 and 0.2436 respectively ;
- The established relationship between the average tensile strength with those of compression, experimentally measured at 7 days of age, is fairly satisfactory with a Pearson correlation coefficient **r** of 0.4992 and a standard error of 2.7880. At 28 days of age, it is largely satisfactory with a Pearson correlation coefficient **r** of 0.9220 and a standard error of 1.1445.

From these results, it should be noted that Eurocode 2 provides a better prediction of the characteristic measured strength at 28 days of age than BAEL 91 modified 99. Despite these differences, the average tensile measured strengths compared to those calculated (according to BAEL 91 revised and Eurocode 2), are of the same order of magnitude. They are used in reinforced concrete to assess deformations and the minimum percentage of steel.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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Nomenclature

Acronyms and abbreviations

AFNOR	French Association for standardization
BAEL	Reinforced concrete in the Limit States
BC1	Combined aggregates based conccrete 1
BC2	Combined aggregates based conccrete 2
BN	Natural aggregates based concrete
BR1	Recycled aggregates based concrete 1
BR2	Recycled aggregates based concrete 2
CA	Combined Aggregate
C/W	Ratio Cement/Water
EN	European Standard

ESP	Equivalent of sand on piston
ESV	Visual Equivalent of sand
LA	Los Angeles Coefficient
LNBTP	National Laboratory of Building and Public Works
MF	Modulus of smoothness
NF	French standardization
ONEA	National Office of Water and Sanitation
RA	Recycled aggregate
Vss	Upper specified value

Symbols

ρ_a	Absolute density (in kg /m^3)
ρ_{ap}	Apparente density (in kg /m^3)
ρ_{rd}	Real density after oven drying
ρ_{rsd}	Real density saturated dry surface
A	Flattening coefficient
d_{min}	Minimum diameter of aggregates (in mm)
D	diameter of the cylinder (in mm)
D_{max}	Maximum diameter of aggregates (in mm)
f_{cj}	Compressive strength at D days (in MPa)
f_{ck}	Characteristic compressive strength (in MPa)
f_{cm}	Average compressive strength (in MPa)
f_{ctm}	Average tensile strength (in MPa)
F_{c7}	Characteristic compressive strength at 7 days of age (in MPa)
F_{c28}	Characteristic compressive strength at 28 days of age (in MPa)
F_{tj}	Tensile strength at D days (in MPa)
F_{t7}	Characteristic tensile strength at 7 days of age (in MPa)
F_{t28}	Characteristic tensile strength at 28 days of age (in MPa)
L	Cylinder length (in mm)
M	Mass of the specimen (in kg)
P	Breaking load value (in N)
r	Pearson correlation coefficient
V	Specimen volume (in kg)