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Behaviour of Self-Compacting Concrete incorporating Natural Perlite used as Part of Cement and as Aggregates

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Abstract

Perlite, a natural glassy volcanic rock could be used as supplementary cementitious material to reduce environmental pollution and the consumption of precious natural resources in the concrete industries. The aim of this work is to assess natural perlite used as 50% aggregates substitution by volume (sand or gravel) and as 10%, 15%, 20% cement substitution in self-compacting concrete. Workability characteristics and mechanical properties were analysed. Results showed that replacing 50% of natural aggregates with 50% of perlite aggregates or substituting cement with 10% of perlite powder generated the best workability characteristics and improved compressive, flexural strength, and elastic modulus of concrete at 28 days. Moreover, the results were combined to develop correlations that prove to be good between mechanical properties of self-compacting. Using perlite as aggregates offers a new source of supply and saves natural aggregates. Also, perlite used as cement substitution helps to reduce PC consumption, cost, and CO_2 emission.

Key words: self-compacting concrete, perlite, fresh properties, mechanical strength, elastic modulus

1 Introduction

Self-Compacting Concrete (SCC) is considered as the most revolutionary development in the construction sector. Since this is based on the elimination of vibration [1, 2] the final product is of higher quality, with the additional benefit that the overall cost of casting is lower [3]. The use of SCC is increasing [4, 5]. Self-compacting concrete contains fine additions which allow it to flow easily and have good workability. Calcareous fillers are often used as additions. However, it is still possible to vary the nature of additions used in mixes of cement. Also, the type of aggregates can be replaced and save natural aggregates. The use of natural perlite as a component of SCC concrete can substantially affect its properties.

Perlite is a glassy volcanic rock that contains approximately 70–75% SiO_2 and 12–18% Al_2O_3. Its 2–6% chemically combined water causes it to expand and become a cellular material of extremely low bulk density when heated to a temperature of 900 °C. Thus, the

expanded perlite is used in various constructional, horticultural, and industrial applications [6, 7]. Due to its glassy structure and high SiO_2 and Al_2O_3 contents, perlite is a pozzolan. Although its pozzolanic characteristics have been mentioned in some limited numbers of technical papers.
Urhan [8] examined the alkali silica and pozzolanic reactions on expanded perlite aggregate concrete. It indicated that even under very unfavourable conditions, once the concrete is made from reactive aggregates or pozzolanic materials, there is always a small amount of alkali silicate gel produced which may cause a subsequent slight expansion of which the magnitude is a function of the mechanical strengths of the concrete. Erdem et al. [9] showed that the perlites possess sufficient pozzolanic characteristics to be used in the production of blended cement.

Terkman & Kantarci [10] investigate drying shrinkage of SCC concrete including mixtures of expanded perlite aggregate at different curing conditions and found that with increasing moisture content and unit quantity of perlite aggregate, drying shrinkage of concrete decreases. Yu et al. [11] indicate that perlite powder has a high pozzolanic effect and is an active mineral admixture (MA) for concrete. Also, Bhuvaneshwari et al. [12] found that for obtaining lightweight concrete, the optimum replacement percentage of sand by Perlite is 10%. The compressive, split tensile, and flexural strength was reduced if the replacement percentage of Perlite will be increased. In addition, using perlite as an aggregate in Portland cement and gypsum plasters for exterior applications and for the fire protection of beams and columns is also very efficient [13]. Johari et al. [14] found that using perlite as an admixture at a proper level of replacing with OPC, generally reduced porosity, mean pore size, and pore diameter of the microstructure of cement paste. Yu et al. [15] studied the influence of perlite powder as an admixture on the pore structure of cement pastes. Their study demonstrated that due to the pozzolanic reaction, it could diminish porosity and pores diameter in cement pastes.

In the work of Esfandiari & Loghmani [16], cement-lime binder was replaced by powder perlite PP at 0%, 5%, 10% 15%, and 20%. They found that the optimum percentage of PP was 6% on 28 and 90-day to obtain maximum compressive strength for SCC concrete. PP as a natural pozzolan is beneficial due to its low price and availability (depending on the region), as well as its ability to reduce the hydration heat and control the shrinkage of concrete mixtures. Nevertheless, its influence on the properties of concrete, including the reactivity (specifically in the early ages), strength, durability, and so on, is still a concern [17]. Sičáková et al. [18] analysed the time development of both compressive and flexural strength, including results of 2, 7, 28 and 90-day testing. They concluded that although perlite blended binders achieved lower strengths compared to conventional binders based on ground granulated blast furnace slag and fly ash, they have a promising potential. Flexural strength of 4.1–6.2 MPa and compressive strength of 18.8–38.5 MPa are sufficient for a number of practical applications and are expected to meet the required limits. Also, their improvement in the later period (90 days) was confirmed. Mansour [19] studied the effect of Algerian natural perlite used as fillers addition on the workability and physical-mechanical properties of steel fibre self-compacting concrete. They showed the beneficial effect of the use of perlite as fillers. Workability properties decreased slightly but an increase of mechanical strengths and elastic modulus was much more marked with the use of the steel hooked fibres. Moreover, El Mir and al. [20] evaluated the effect of waste perlite powder along with its combination with

limestone fillers, metakaolin, and silica fume on durability and long-term transport properties of self-consolidating concrete. They found that water permeability, carbonation, and chloride ion migration curtailed when perlite powder concentration reached 220 and 260 kg/m^3. In contrast, the resistance against freeze/thaw remarkably improved. Mansour et al. [21] showed the performance of powder perlite use as cement substitution on workability, physical-mechanical properties of self-compacting concrete by destructive and non-destructive tests. They concluded that the association of 5% granite and 5% perlite has generated satisfactory workability and mechanical properties which approach those of the SCC reference concrete.

The objective of this work is to assess the natural perlite derived from the deposit of the company Bental located near Hamame Boughrara northwest of Tlemcen region (Algeria) when it is used as cement substitution varying from 10%, 15% to 20%, also used as aggregates (sand or gravel) in self-compacting concrete with a replacement rate of 50%. This can help solve the problem of lack of aggregates and in particular the use of alluvial aggregates. In this work, six formulations of self-compacting concrete were studied. Fresh properties such as slump flow, filling capacity, and resistance to segregation; also, hardened properties as specific gravity, compressive, flexural strength, and elastic modulus were determined. Moreover, obtained results were combined to develop correlations between mechanical properties of the destructive and non-destructive tests.

2 Materials and Methods

2.1 Materials

Cement: CPJ-CEM II/A 42.5 Portland cement from the M'sila cement plant is used. It is obtained by the finely ground mixture of clinker and additions (gypsum and limestone) according to Algerian standard NA 442. Its specific gravity is 3.1 g/cm^3 and its specific surface area Blaine SSB is 3900 cm^2/g. Also, at 28 days, its compressive and flexural strength are 49 MPa and 8 MPa respectively. As an addition in the self-compacting concrete, a rate of 10% of limestone fillers is used. The limestone is characterized by high chemical purity and high whiteness. Its specific area Blaine is 7300 cm^2/g, and its specific gravity is 2.66 g/cm^3.

Perlite: The used perlite is of volcanic origin manually extracted from the deposit located in the northwest of Algeria. This grey-coloured perlite was extracted in the form of pieces of rock with diameters varying from 20 to 40 cm. The perlite rock was crushed and then steamed for 24 hours at a temperature of 80°C to remove any moisture, then crushed, grinded, and sieved at 80 µm when it was used as cement substitution. Perlite powder incorporating cement has a Blaine specific surface area of 5400 cm^2/g and specific gravity of 2.38 g/cm^3. The chemical compositions of cement, limestone, and powder perlite are shown in Table 1. Moreover, the X-ray diffraction pattern was established for the natural powder perlite (Figure 1).
Chemical composition shows that the rate of silica (64.44%) contained in perlite indicates the siliceous nature of perlite. In addition, the oxides rate [SiO_2(%) + Al_2O_3(%) + Fe_2O_3(%)] is 80.89% corresponding to a value according to ASTM C 618 standard specification for natural pozzolans (min 70%) [22]. X-ray analysis of perlite shows a remarkable hump which signifies a high content of amorphous silica and peaks that characterize the crystalline phases such as

montmorillonite, quartz, albite, and muscovite (Figure 1). As a result, the chemical composition of the perlite shows the siliceous nature, their XRD pattern shows the amorphous structure, conformance of the perlite to the standard specification for natural pozzolans, ASTM C 618, and the previous studies [7, 23, 24] on the pozzolanic properties of the perlite prove from many aspects that perlite possesses certain pozzolanic characteristics and can be used as a cement replacement in concrete.

Aggregates: Used natural sand was a mixture of natural dune fine sand (DS) and river sand (RS). Different natural gravel types of class 3/8 mm, 8/15 mm were also used. Moreover, the perlite aggregates were obtained by crushing natural perlite rock to the desired dimensions of sand (0/4 mm) and gravel (3/8 mm, 8/15 mm) (Figure 2). The physical properties of natural aggregates and perlite aggregates are displayed in Table 2.

2.2 Methods

2.2.1 Concrete mixtures

Six SCC main groups of mixes were prepared with the binder dosage constant (430 kg/m^3) and 2% of superplasticiser (MEDAFLOW 30), having a density of 1.07 and chlorine content < 0.1 g/l; also, using 0.9 fixed gravel-to-sand ratio, 0.38 water to binder ratio and by using perlite rock as aggregates replacement (Perlite Sand PS or Perlite Gravel PG) and Perlite Powder PP as cement substitution at the rate of 10%, 15% to 20%. The SCC concretes are specified as PN0 (100% natural aggregates, 0% Perlite) which is the control SCC concrete, PS50 (50% RS(0/4 mm) natural river sand +50% PS(0/4 mm) Perlite sand), PG50 [50% (NG3/8) Natural Gravel+50% (NG8/15) Natural Gravel + 50% (PG3/8) Perlite Gravel + 50% (PG8/15) Perlite Gravel], PP10 (90% cement PC+10% Perlite Powder), PP15 (85% cement PC+15% Perlite Powder), PP20 (80% cement PC+20% Perlite Powder). The substitution of natural sand RS 0/4 mm and natural gravel NG3/8 or NG8/15 was carried out by volume because the densities of (3/8 and 8/15) perlite gravel and (0/4 mm) perlite sand are different from (3/8 and 8/15) natural gravel and (0/4 mm) natural sand (Table 2). Therefore, the weights of perlite aggregates and natural aggregates are different. Mix proportions of SCC mixtures are presented in Table 3.

2.2.2 Procedure

The bulk density ρ_f and ρ_h is measured in the fresh and the hardened states respectively according to the standard NF EN 12350-6 [30] and NF EN 12350-7 [31] respectively, for different SCC formulations. The fresh properties of performed SCC were evaluated from several tests such as slump flow test (NF EN 12350-8) [25], L-Box test (NF EN 12350-10) [26], and sieve stability test (NF EN 12350-11) [27] by determining the slump flow, filling rate, and segregation resistance respectively, whose values must be in accordance with the recommendations given by the European Federation of National Trade Associations EFNARC [28]. Otherwise, for mechanical tests and for each mixture, three prismatic SCC concrete samples (70x70x280 mm) and three cylindrical samples (110x220 mm) were manufactured according to standard NF EN 12390-2 [29]. After 24 hours, the samples were stored in water at 20 °C ± 2 °C. SCC was then tested in compression (NF P18-406) [30] and flexural (NF P18-407) [31] at maturities 7 and 28 days. An ultrasonic non – destructive

testing was used to detect cracks and other discontinuities in SCC concrete [32, 33]. The ultrasonic non-destructive testing technique (NFP 18-418) [34] is typically based on the measurement of the ultrasonic velocity passing through cylindrical samples. This velocity is closely related to mechanical properties and, more directly, to the modulus of elasticity. By using velocity, the elastic modulus of SCC concrete can be calculated with the Equation (1) given by Gupta et al. [35]:

$$E_d = (\rho . Vus^2/g).10^{-2} \quad (1)$$

Where E_d is the dynamic modulus of elasticity (GPa), Vus is the ultrasonic pulse velocity (km/s), ρ is the specific density (kg/m^3), and g the gravitational acceleration (9.81 m/s^2).

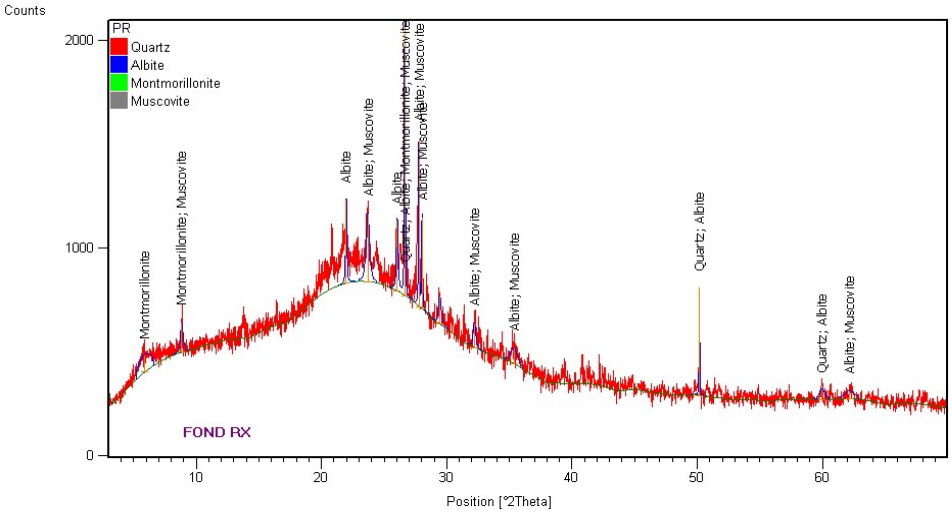


Figure 1: X-ray diffraction of the perlite (Cu kα filter Ni)

Table 1: Chemical composition of cement PC, perlite, and limestone (%)

Oxides	Cement PC	Perlite	Limestone
SiO_2	16.96	64.44	4.83
AL_2O_3	4.68	14.94	1.04
Fe_2O_3	2.98	1.51	0.37
CaO	60.19	5.79	51.73
MgO	1.84	1.33	0.46
K_2O	0.61	3.40	0.14
Na_2O	0.093	1.87	0.08
SO_3	1.65	0.88	0.08
Cl-	0.017	0.41	0.03
LOI	9.87	-	41.17



Figure 2: Stages of rock perlite recycling

Table 2: Physical properties of natural aggregates and perlite aggregates

Aggregate	DS	RS	NG3/8	NG8/15	PS0/4	PG3/8	PG8/15
Absolute density g/cm^3	2,61	2,66	2,63	2,66	2,43	2,44	2,46
Apparent density g/cm^3	1,31	1,53	1,42	1,42	1,28	1,41	1,43
Water content %	4.75	3.85	0.40	0.40	0.85	0.35	0.35
Sand equivalent %	69	72	-	-	76	-	-
Los Angeles coefficient %	-	-	24.3	24.3	-	27.2	27.2
Micro Deval coefficient %	-	-	26.8	26.8	-	29.3	29.3
Water Absorption %	0.96	0,95	0,64	0,60	0,75	0,66	0,67
Porosity %	2.46	2.36	1.74	1.62	1.98	1.73	1.73

Table 3: Mix proportions of SCC mixtures (kg/m^3)

Constituents	PN0	PS50	PG50	PP10	PP15	PP20
Cement	430	430	430	387	365.5	344
Limestone fillers	43	43	43	43	43	43
Perlite	-	-		43	64.5	86
DS (fine sand)	348.43	348.43	348.43	348.43	348.43	348.43
RS (0/4mm)	574.48	287.24	574.48	574.48	574.48	574.48
PS (0/4mm)	-	262.41	-	-	-	-
NG 3/8	275.72	275.72	137.86	275.72	275.72	275.72
NG 8/15	557.77	557.77	278.88	557.77	557.77	557.77
PG 3/8	-	-	127.91	-	-	-
PG 8/15	-	-	257.92	-	-	-
Efficient Water	174,49	174,49	174,49	174,49	174,49	174,49
Superplasticizer	7,51	7,51	7,51	7,51	7,51	7,51
ρ_h (kg/m^3)	2254	2226	2228	2235	2233	2232

Table 4: Workability characteristics of SCC concrete

Constituents	PN0	PS50	PG50	PP10	PP15	PP20
ρ_f (kg/m^3)	2373	2322	2332	2365	2359	2354
Slump flow (cm)	71	69	68	70	62	60
Passing ability	0.9	0.85	0.82	0.84	0.81	0.80
Milt- Sieve stability (%)	4	4.2	4.1	5	6.2	7.1

3 Results and discussion

3.1 Apparent bulk density of SCC concretes

Results in Table 3 and Table 4 show that the densities of SCC concrete are slightly less than that of the control SCC. For example, a low reduction of 2% was noted for the fresh SCC and 1.2% for the hardened SCC containing 50% sand, this is due to the fact that the quantity of sand (natural and perlite) in PS50 is with near 25 kg less than in PN0 because of the density of perlite sand which is lower than that of natural sand (Table 2).

3.2 Fresh properties of SCC

From the results of fresh properties, slump flow values are between 60 cm and 70 cm for all SCC containing perlite (Table 4), and no segregation was observed visually. These values are in agreement with the recommendations suggested by EFNARC for self-compacting concrete [28]. All SCCs are classified as SF2 except PP15 and PP20 which are classified as SF1. It is noted that the introduction of perlite as aggregates (sand or gravel) or as cement substitution decreased the slump flow of SCC. The slump flow of the control SCC and SCC with 10% of perlite are almost the same. But, beyond 10% of perlite, a remarkable slump flow decrease was obtained because the mix cement matrix absorbed more water. This decrease can be up to 15% for a cement substitution of 20% perlite. The reduction in slump flow is probably due to the high fineness of perlite compared to that of cement, which can absorb the water and consequently decreases SCC flowability. Moreover, perlite used as aggregates slightly decreases the slump flow and the fluidity of PS50 and PG50. The reduction was 3% and 4% respectively. In conclusion, the replacement of half of the natural aggregates by perlite aggregates, even better substituted the cement with 10% of natural powder perlite and generates good fluidity of SCC which aligns with those of the control SCC.

The L-box test is operated through the passing ability (ratio H_2/H_1) which must be greater than 0.8 [28]. The obtained values were in conformity with EFNARC requirements for all SCCs, therefore their mobility in a confined environment is assured. This allows them to flow through the reinforcements correctly. L-Box test results ≥ 0.80 come under PA1 classes with 2 rebars and the test results ≥0.80 come under PA2 classes with 3 rebars. This is means that the risk of blockage is avoided. All SCCs were classified as PL2. Compared to SCC control, the passing ability of PP15 and PP20 decreased more than for the other SCC variants. The reduction was 9% and 10%.

Concerning the segregation of SCCs, the sieve stability test is the essential point to be verified. This test is used to measure the milt corresponding to the ability of self-compacting concrete to segregation resistance. Obtained values ranging from 4% to 7.1% are acceptable (<15%) according to EFNARC requirements of self-compacting concrete [28]. This means that all SCCs are homogeneous stable and classified as SR2. The concrete PN0 is characterized by high stability (lower limit = 4%) and consequently a high resistance to segregation and to bleeding. It seems that using perlite as aggregates did not affect the stability of SCC. When the perlite is used as cement substitution, PP10, PP15, and PP20 are homogeneous but less stable than PN0. This is due to the increase of the amount of perlite fines in SCC which facilitates the passage through the sieve and increases the milt weight [38].

Moreover, the introduction of the perlite decreases the specific gravity ρ_f of fresh SCCs. This is due to fact that the specific gravity of perlite used as aggregates or as cement substitution is smaller than that of natural aggregates or cement respectively. The smallest reduction is obtained for SCC containing 10% of powder perlite.

3.3 Compressive strength of SCC concretes

Results of compressive strength of SCCs at different maturities are illustrated in (Figure 3). The compressive strength of all SCCs increases over time; also, it decreases when 50% of natural aggregates (sand or gravel) were replaced by 50% of perlite aggregates.

The reduction is not significant, at 28 days; it is limited at 6.6% and 4.2% for the SCC containing 50% of perlite sand and 50% of perlite gravel respectively. It is probably due to the fragility of the aggregates of perlite rock compared to natural aggregates. On the other hand, the introduction of perlite as cement substitution increases and exceeds that of control SCC. Indeed, at 28 days, a gain of strength of 8.7% and 2% was obtained when the cement was substituted by 10% and 15% of perlite powder respectively.

The increase of compressive strengths is due to the filling effect and pozzolanic reaction [39]. But, for the SCC containing 20% of perlite powder, a reduction of compressive strength of 7.5% was noticed. This can be explained by the lower cement PC content in PP20 SCC concrete. In the other words, this is due to the decrease of the main tricalcium silicate C_3S and bicalcium silicate C_2S cement minerals which are the first responsible for the development of the mechanical strengths. Also, the water destined to cement wetting was mobilized by the perlite due to its high fineness, which delayed the hydration process, therefore a decrease in strength has been recorded. A similar result was found in the study of Yu et al. [11].

3.4 Flexural strength of SCCs

Figure 4 shows the flexural strength of SCCs. It increases at maturities of 7d and 28d for all SCCs. The rate of 50% perlite sand or 50% perlite gravel affects the flexural strength of SCC with a loss of 14% and 6.3% respectively at 28 days. Furthermore, 10% of perlite rate substituting the cement increases flexural strengths which exceed those of SCC control. A gain of 3.3% is obtained at 28 days. These results confirm those of compressive strengths.

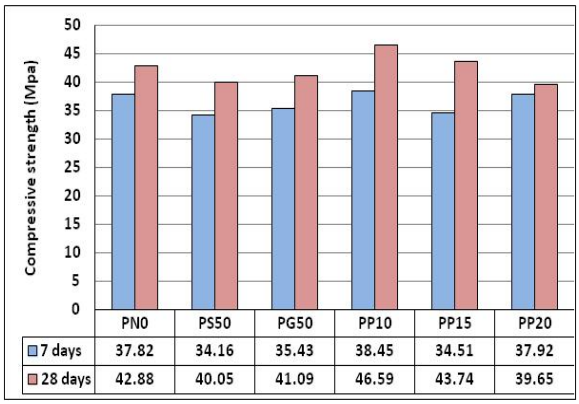


Figure 3: Experimental compressive strength of SCCs

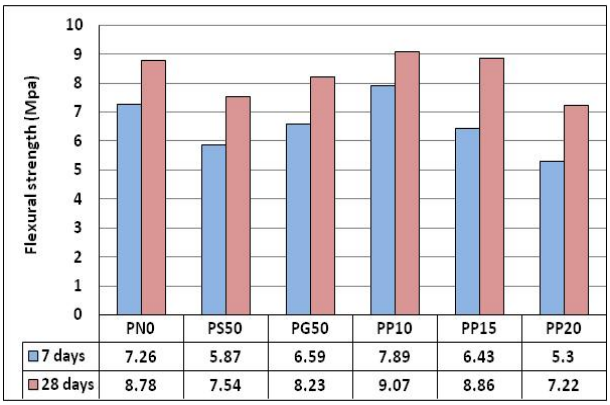


Figure 4: Flexural strength of SCCs

3.5 Ultrasonic pulse velocity of SCCs

The value of the ultrasonic velocity (V_{us}) is another relevant indicator for the microstructure. This velocity is highly influenced by the presence of voids within the material. The results of the ultrasonic velocity of SCC specimens at 28 days are given in Table 5. It is shown that the replacement of 50% of natural gravel by perlite gravel did not affect the velocity. But the velocity increases to 7% when cement is replaced by 10% of perlite powder. This is due to the fineness and reactivity of the perlite powder with the porthlandite released during hydration of the cement, to produce hydrated calcium silicates C-H-S which densify the cement matrix. While the compactness and the density of concrete increased, the ultrasonic wave velocity and strength of concrete increased together [40, 41, 42]. Moreover, the quality of all SCCs was considered as generally good. Indeed, the ultrasonic wave velocity of a good quality concrete should be between 4100 m/s and 4700 m/s [41].
A relationship between experimental compressive strength $R_{c(exp)}$ at 28 days of all SCCs and ultrasonic velocity V_{us} was obtained (Figure 5). It is in the exponential form with a coefficient $R^2 = 0.7319$. This relation is expressed by Equation (2):

$$R_{c(exp)} = 0.8356e^{0.0009Vus} \quad (2)$$

The model of this correlation is in the form $R_c = a.e^{b.Vus}$, where the compressive strength R_c can be directly determined from the ultrasonic velocity *Vus*. The form of this model is in agreement with the theoretical formula Rilem standards.

Table 5: Ultrasonic velocity and dynamic modulus of SCCs at 28 days.

SCC concrete	PN0	PS50	PG50	PP10	PP15	PP20
Ultrasonic velocity *Vus* (m/s)	4330	4250	4340	4370	4350	4230
Dynamic modulus E_d (MPa)	42260	40210	41960	42690	42262	39940

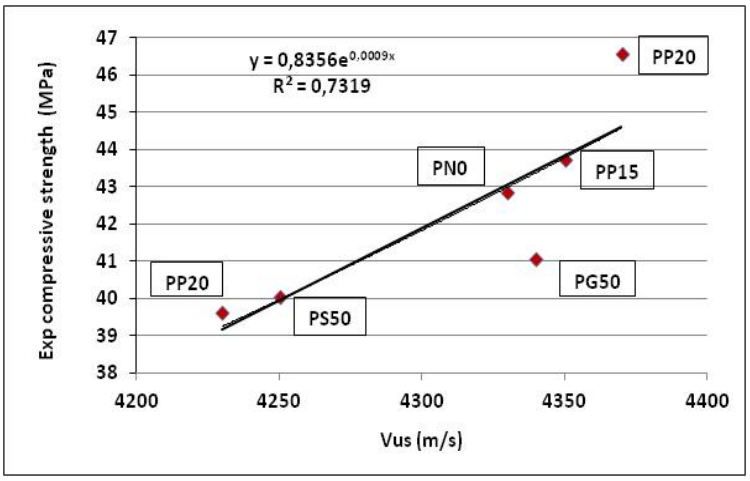


Figure 5: Relationship between experimental compressive strength and ultrasonic velocity

Moreover, the velocity can be used to calculate the compressive strength $R_{c\ (US)}$ at 28 days using Equation (3):

$$R_{c\ (US)} = 0.08177e^{0.00147Vus} \quad (3)$$

In this study, compressive strength obtained experimentally by compressive test at 28 days and by using the ultrasonic velocity according to equation (3), are compared as shown in Figure 6. The two strengths evolve similarly and are mostly aligned especially at 28 days. They are in agreement. Indeed, a good polynomial relationship between $R_{c(exp)}$ and $R_{(US)}$ was obtained with coefficient $R^2 = 0.8751$ as shown in Figure 7 and expressed by Equation (4).

$$R_{c\ (exp)} = 0.131R^2_{c(US)} - 11.379R_{c\ (US)} + 285.37 \quad (4)$$

Moreover, by comparing the two expressions of the strength as a function as the ultrasonic velocity given by equation (2) obtained by destructive test and the theoretical equation (3), a relative variation of the strength was obtained by the two equations ranging from 8% to 15%. This leaves us to conclude that equation (2) can be used to determine the compressive strength of SCC.

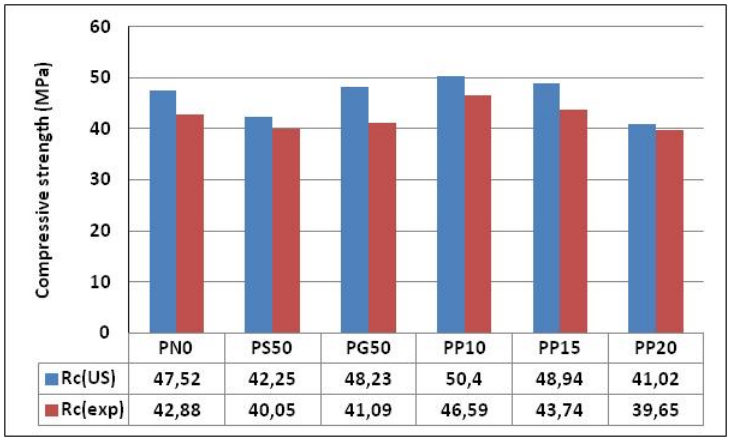


Figure 6: Ultrasonic and experimental compressive strength at 28 days of SCCs

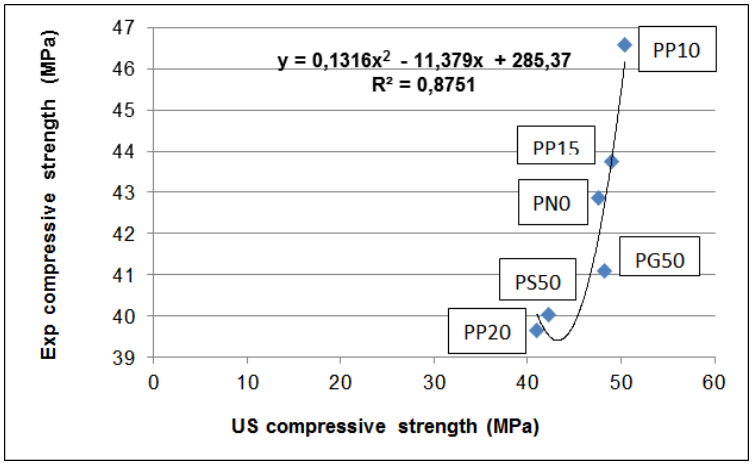


Figure 7: Relationship between experimental and ultrasonic compressive strength

3.6 Elastic modulus of SCC

Ultrasonic velocity depends strongly on the mechanical properties of the material, especially elastic modulus. From the values of ultrasonic velocity, the dynamic modulus of elasticity E_d was determined using Equation (1). On the other hand, the elastic modulus was also calculated by Equation (5) according to BAEL1991 standards [43]:

$$E_{(BAEL91)} = 11000\ (R_{cj})^{1/3} \tag{5}$$

R_{cj}: compressive strength at j day's old concrete.

$E_{(BAEL)}$ elastic modulus was determined for all SCCs at 28 days and compared to dynamic modulus E_d. The results illustrated in Figure 8 showed that for the two elastic moduli, incorporation of the rate of 10% and 15% of perlite powder used as cement substitution increases slightly (1%) elastic modulus of the SCC. Otherwise, the replacement of natural aggregates by 50% of perlite aggregates did not significantly affect the modulus of elasticity. In fact, a slight decrease of 1% and 5% were obtained for SCC containing perlite sand and perlite gravel respectively. This is means that the perlite aggregates are of good quality with high elastic modulus and present a good adhesion with the cement matrix.

In addition, $E_{(BAEL)}$ modulus varied similarly as the E_d but remained smaller than the latter. Compared to E_d, $E_{(BAEL91)}$ modulus is underestimated.
A relationship between the two elastic modulus of elasticity of all SCCs was obtained (Figure 9). The value of coefficient (R^2) which is 0.9588 indicates a very good polynomial relationship between the elastic modulus $E_{(BAEL91)}$ and the dynamic modulus E_d described by Equation (6).

$$E_{(BAEL91)} = 0.0007E_d^2 - 53.137E_d + 1e^6 \tag{6}$$

This relationship is interesting since it is possible to determine the $E_{(BAEL91)}$ modulus from the dynamic elastic E_d modulus.

Another relationship can be obtained by connecting $E_{(BAEL91)}$ and the ultrasonic velocity of SCCs. Figure 10 illustrates this relation which showed a good correlation between these parameters with coefficient $R^2 = 0.868$. It is described by Equation (7):

$$E_{(BAEL91)} = 0.1804 V_{us}^2 - 1538.5 V_{us} + 3e^6 \quad (7)$$

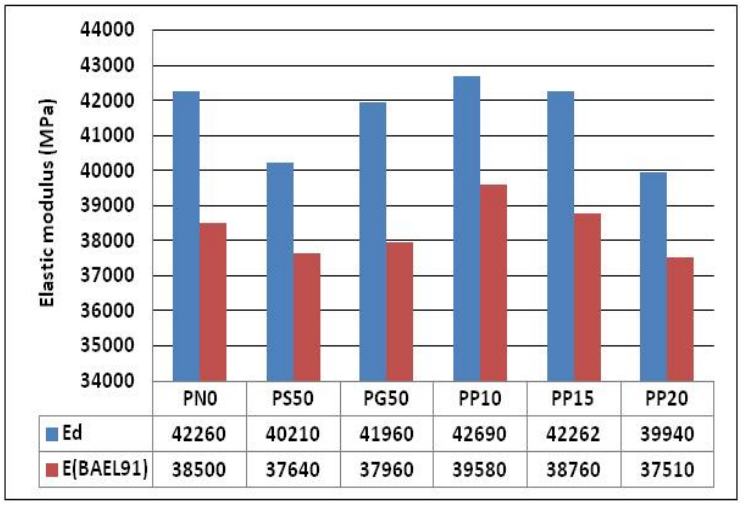


Figure 8: Dynamic and BAEL91 elastic modulus of SCCs

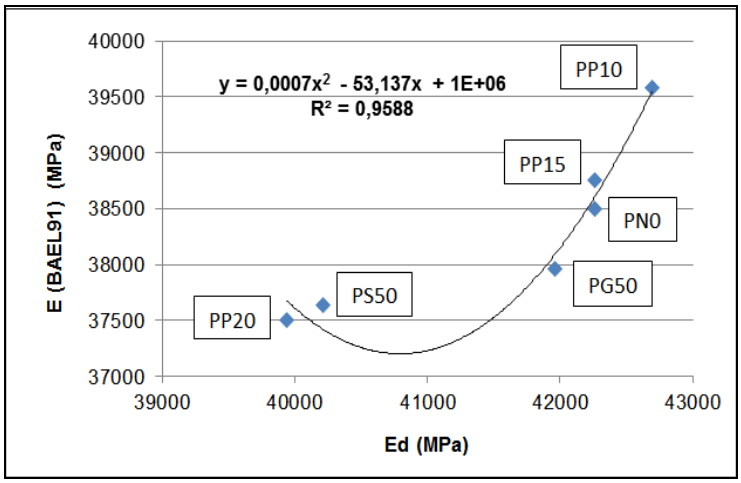


Figure 9: Relationship between $E_{(BAEL91)}$ and E_d modulus

This relationship has a polynomial form which is in adequacy with the shape of the expression of the dynamic modulus E_d (1). From these results, it is possible to calculate the modulus $E_{(BAEL91)}$ from the value of the ultrasonic velocity determined by a non-destructive test.

On the one hand, a relationship between the compressive strength determined by the ultrasonic velocity of the non-destructive test and the elastic modulus (E_d, $E_{(BAEL91)}$) was

established and illustrated in Figure 11. On the other hand, a relationship between the experimental compressive strength determined by the destructive test and elastic modulus (E_d, $E_{(BAEL91)}$) is illustrated in Figure 12.
Good polynomial correlations were obtained between the elastic modulus E_d or $E_{(BAEL91)}$ and the ultrasonic compressive strength or experimental compressive strength respectively with coefficient R^2 ranging from 0.875 to 1 as expressed by Equations (8, 9, 10, 11).

$$E_d = -89.6\ R^2_{c(exp)} + 8092.4 R_{c(exp)} - 1398 \quad (8)$$

$$E_{(BAEL91)} = -2.34 R^2_{c(exp)} + 500 R_{c(exp)} + 2137 \quad (9)$$

$$E_d = -10.03\ R^2_{c}(us) + 1214.3 R_c(us) + 6932.8 \quad (10)$$

$$E_{(BAEL91)} = 37.8\ R^2_c(us) - 3265.7\ R_c(us) + 107884 \quad (11)$$

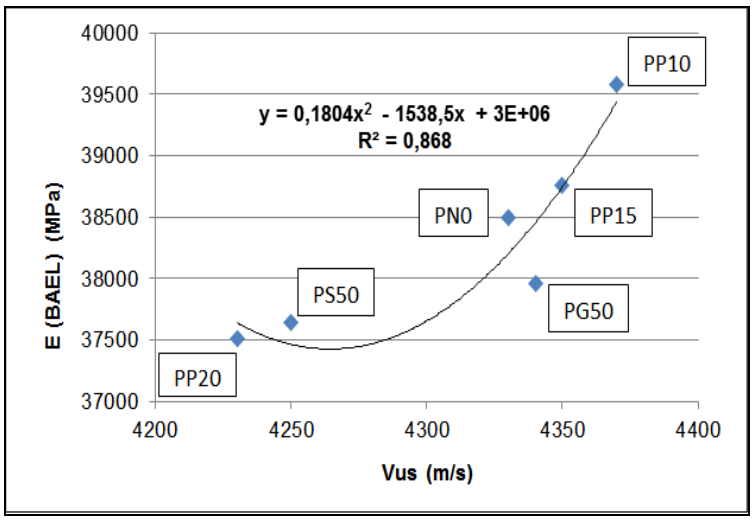


Figure 10: Relationship between $E_{(BAEL)}$ modulus and ultrasonic velocity

From the correlations found in this study, it is worth noting that it is interesting to combine results of destructive and non-destructive tests to determine the mechanical properties of SCCs. For example, $E_{(BAEL91)}$ modulus can be determined from dynamic modulus at 95.88% and from the ultrasonic velocity $V_{(us)}$ at 86.8%. In addition, the experimental compressive strength value can be estimated from the strength calculated with the ultrasonic velocity at 87.5%.

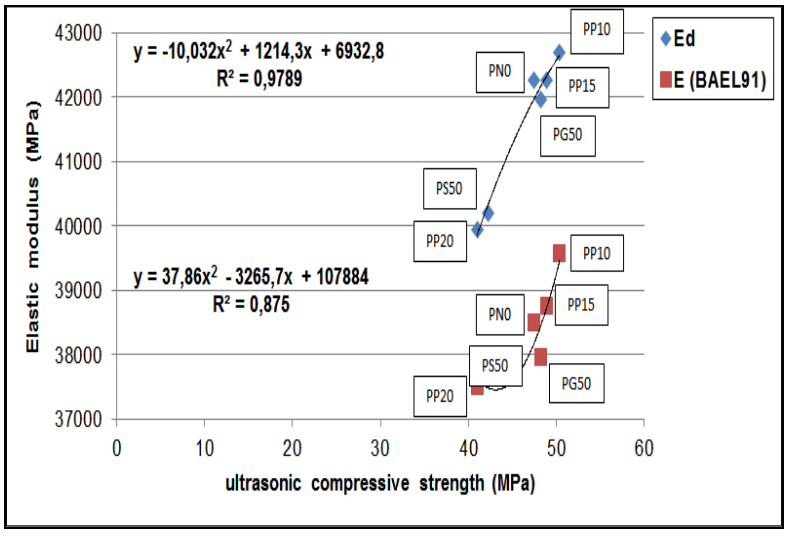


Figure 11: Relationship between elastic modulus *Ed*, $E_{(BAEL91)}$ and ultrasonic compressive strength

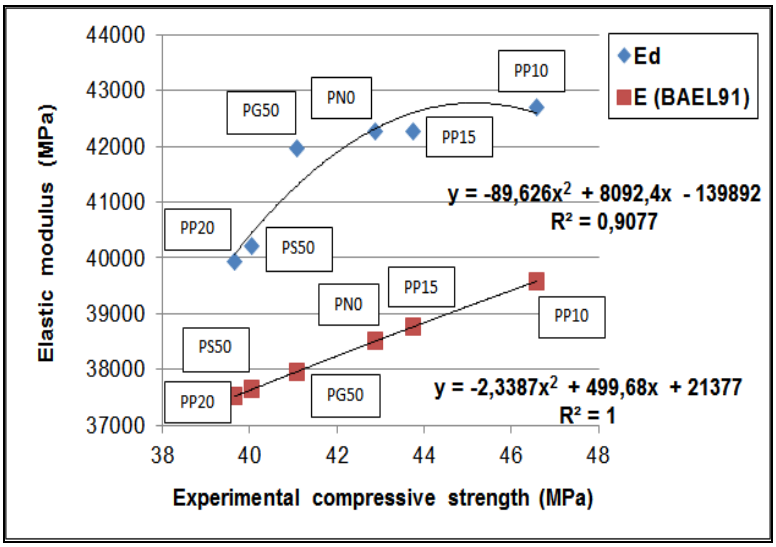


Figure 12: Relationship between elastic modulus E_d, $E_{(BAEL91)}$ and experimental compressive strength.

4 Conclusion

This study focused on the valorisation of natural volcanic rock, the perlite from western Algeria used as a component of the self-compacting concrete such as cement substitution and as aggregates. Based on obtained results, the following conclusions can be drawn:

- Investigated natural perlite has a specific area greater than that of cement, contains a high rate of silica, and has an amorphous structure. Therefore, it possesses sufficient pozzolanic characteristics to be used in cement and concrete.
- Values of fresh properties of performed SCCs are in agreement with the requirements of EFNARC for self-compacting concrete.
- Replacement of 50% of natural sand by 50% of perlite sand or substitution of cement by

10% of perlite powder improves the fresh properties.
- A gain of compressive and flexural strength of 8.7% and 3.3% respectively were obtained when the cement is substituted by 10% of perlite powder at 28 days.
- Concerning the non-destructive test, the ultrasonic velocity increases to 7% when the cement is replaced by 10% of perlite powder.
- From the ultrasonic velocity values, the quality of perlite SCC concretes can be considered as generally good.
- Replacement of natural aggregates by 50% of the perlite aggregates (sand or gravel) in self-compacting concrete can offer a new source of supply and save natural aggregates, especially with the problem of depletion of natural resources that meets the aggregates market.
- In addition, the use of 10% of perlite as the substitution in blended cement can be beneficial and help to reduce the PC consumption, therefore, cost and CO_2 emission especially for countries that produce considerable amounts of cement.
- A model of correlation in exponential form is obtained between the experimental compressive strength and ultrasonic velocity ($R_{c(exp)} = 0.8356e^{0.0009Vus}$) with a coefficient $R^2 = 0.7319$. The form of this model is in agreement with the theoretical formula given by Rilem standards.
- A good polynomial relationship between experimental compressive strength $R_{c(exp)}$ and strength determined using ultrasonic velocity $R_{(US)}$ is obtained with a coefficient $R^2 = 0.8751$. Indeed, the two strengths evolve similarly and are mostly aligned especially at 28 days. So, it is interesting to determine the compressive strength of concrete with an ultrasound test.
- The dynamic elastic modulus E_d can be directly determined from the experimental compressive strength $R_{c(exp)}$ or ultrasonic strength $R_{c(US)}$. Good polynomial relationships were obtained with a coefficient R^2 of 0.9077 for the relation between E_d and $R_{c(exp)}$, also 0.9789 for E_d and $R_{c(US)}$.
- Modulus of elasticity $E_{(BAEL91)}$ can be directly determined respectively from the experimental compressive strength $R_{c(Exp)}$ and ultrasonic strength $R_{c(us)}$ with a correlation coefficient $R^2 = 1$ and 0.875 respectively.
- $E_{(BAEL91)}$ modulus can be determined from the dynamic modulus with coefficient $R^2 = 0.9588$ and from the ultrasonic velocity *Vus* with $R^2 = 0.868$. In addition, the compressive strength value can be estimated from the strength calculated with the ultrasonic velocity at 87.5%.
- Based on study results, ultrasonic velocity can be considered potentially useful in predicting the compressive strength and the elastic modulus of the SCC.
The use of these correlation curves allows a better estimate of the actual strength of SCC concrete as well as its modulus of elasticity compared to the usual curves recommended by the manufacturers of the devices or those established by other authors. Therefore, the establishment of a correlation between two parameters must be based on conditions appropriate to the study.

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