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Physico-mechanical properties of aerated cement composites containing shredded rubber waste

A. Benazzouk *, O. Douzane, K. Mezreb, M. Quéneudec

Laboratoire des Technologies Innovantes (EA 3899), Université de Picardie Jules Verne, IUT Département Génie Civil,
Avenue des Facultés, 80025 Amiens, France

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Abstract

The study reported in this paper was undertaken to investigate the physico-mechanical properties of aerated cement composite with rubber waste particles, in order to produce usable materials in cellular concrete applications. The material, containing different amounts of rubber particles as replacement to cement by volume, was aerated by artificially entrapping air voids by means of a new proteinic air-entraining agent. Results from tests performed on fresh composite have shown many attractive properties, such as improvement in workability and air-entrained with high stability of air-bubbles in the matrix. A study conducted on hardened composite properties has indicated a significant reduction in sample unit weight, thereby resulting in a level of compressive strength compatible with a load-bearing wall. The reduction in flexural strength was lower than that in compressive strength. The results have shown that the presence of air voids and rubber particles in the matrix reduces the elasticity dynamic modulus, which indicates a high level of sound insulation of the composite. This study has also highlighted the effect of the proteinic air-entraining agent on the cement matrix/rubber interaction system, as regards the composite's mechanical strength.

Keywords: Rubber wastes; Cement composite; Rubber particles; Proteinic air-entraining agent; Physico-mechanical properties

1. Introduction

Aerated concretes are materials belonging to the lightweight concrete classification, in which air voids are artificially entrapped in the matrix by means of either chemicals (metallic powders such as Al, Zn and H_2O_2), mechanical agents (foaming agents) or aerating agents. The aim behind their use is to significantly reduce material density. The key advantage of aerated concrete is its light weight, which can yield mechanical characteristics that comply with the specifications issued for building applications. Through appropriate production methods, aerated concrete featuring a wide range of densities (300–1800 kg/m^3) may be obtained, in comparison with 2300 kg/m^3 for traditional concrete.

Aerated concretes also provide a high degree of thermal insulation due to their porous structure. Depending upon their physico-mechanical characteristics, these concretes can be employed as a suitable material for insulated load-bearing walls. In addition, the small-entrained air voids are not likely to generate increased water permeability [1]. Air entrainment is primarily recommended to improve the freeze-thaw resistance of hardened concrete [2]. Air voids act as empty chambers in the matrix to allow for both freezing and migrating water to enter, thereby relieving hydraulic pressure and preventing damage to the concrete.

Al-Rim [3] investigated the properties of lightweight clayey-concrete, manufactured by entraining air voids into the matrix, through introducing both aluminum powder and a proteinic air-entraining agent. It was found that the materials highlighted a number of interesting mechanical and thermal properties and demonstrated the capacity to be used with insulated load-bearing walls. A study of the

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* Corresponding author. Tel./fax: +33 3 22 53 40 16.
E-mail address: amar.benazzouk@u-picardie.fr (A. Benazzouk).

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composite's behavior, at various water saturation states, has displayed the relative importance of macroporosity in comparison with hydraulic transport and thermal properties [4]. An optimization study of the properties of aerated clayey-concrete, produced by entraining air voids using a proteinic aerating agent, was investigated by Ruzicka [5]. Research carried out by Kearsley and Wainwright [6] focused on the mechanical properties of foamed concrete. Results indicated that up to 67% of the cement could be replaced by fly ash without any significant reduction in strength. The authors also investigated the porosity-permeability and porosity-compressive strength relationships of foamed concrete containing various volume contents of fly ash. They presented a mathematical model that was developed to describe these relationships [7,8]. Other studies have demonstrated that due to its closed pore structure, aerated concrete features a high level of fire resistance, as compared to dense concrete [9].

The work presented herein focuses on the feasibility of using shredded rubber waste as an aggregate in cement composite, to develop usable materials in cellular concrete applications. This study has been conducted within the scope of the recent introduction of European Union directives that include significant restrictions on the disposal of used tires in landfills, stockpiles, or illegal dumping grounds in favour of alternatives oriented toward materials and energy recovery. Highway construction provides a significant market potential for waste tires recycling. Along these lines, extensive studies have been conducted on waste tire modified Portland cement concrete [10–14]. The literature about the use of tire rubber particles in cement-based materials focuses on the use of tire rubber as an aggregate in concrete and evaluates only the mechanical properties. Results have indicated that rubberized concrete mixtures posses lower density, increased toughness and ductility, higher impact resistance, lower compressive and splitting tensile strengths, and more efficient sound insulation. A recent study focusing on the cement composite-based tire rubber particles has revealed some interesting mechanical and hydraulic transport properties [15]. Despite the significant reduction in compressive strength, the composite satisfies the basic requirement of construction materials. In addition, the incorporation of rubber particles in cementitious matrix tends to restrict water absorption. Although several work has been done on the mechanical properties of cement composite containing rubber aggregates, no work has been previously reported on the aerated composite by artificially entrapping air voids.

The idea is to use rubber waste particles, as a raw material, to develop new lightweight cement composite based rubber waste particles. In this paper, we report the study of the mechanical properties of the composite containing various rubber volume ratios [15]. The specimen was aerated by artificially entrapping air voids by means of a proteinic air-entraining agent, in order to use it in cellular concrete applications. An experimental test program was conducted mainly to investigate the properties of fresh composite included slump and air entrainment. The tested properties of hardened composite were the dry unit weight, compressive strength, flexural strength and elasticity dynamic modulus, all of them measured at 28 days. The rubber volume ratio ranged from 0 to 50%. The results have been compared with those obtained from a non-aerated composite.

2. Materials and experimental testing

2.1. Materials

Rubber particles used in this study have been obtained from mechanical shredding of rubber automotive industry waste. This waste comprises rubber particles of less than 1 mm in size and contains approximately 20% by volume of polypropylene fibers as well. The absolute density of this rubber waste particles is 430 kg/m^3.

Proteinic air-entraining agent used was "Vepro 95 BHF" in the powder form, consisting of atomized and thermally stabilized bovine hemoglobin manufactured by the Vapran Company.

The cement used in this study was CPJ CEM II 32.5 in accordance with Standard NF P 15-301 [16]. Both the rubber particles and cement were initially dry-mixed in a planetary mixer. The volume ratio of rubber ranged from 0% to 50%, as replacement to cement in mixtures. Total mixing water had been adjusted so as to achieve constant workability for all composites (i.e. slump on the order of 90–100 mm). The total mixture was mixed for 3 min. Table 1 gives the correspondent values of water–cement ratio (w/c) for all mix compositions. Up until obtaining a uniform mixture, the required amount of proteinic air-entraining agent, as 1% by weight of cement, was added and the mixture was mixed for another 1 min. The resultant material was first characterized in its fresh state. For measurements of the hardened composite, prism samples of $40 \times 40 \times 160$ mm in size were prepared and moist-cured for 28 days at 20 ± 2 °C and 98% relative humidity both before and after demolding. Prior to testing, all the specimens were dried in a drying oven at 70 ± 2 °C until reaching constant mass. The composites resulting from application of this process have been designated cement–rubber composite (CRC) and aerated cement–rubber composite (ACRC), respectively. Results should be reported in Section 3. The physico-mechanical properties of CRC samples, for various rubber volume ratios, are listed in Table 1 [15].

2.2. Test procedure

The properties tested on the fresh ACRC sample included slump and air entrainment. The test procedures used for slump test and pressure method were in accordance with Standards NF EN 12350-2 [17] and NF P 18-353 [18], respectively. The properties tested on the hardened composite included dry unit weight, as determined by

Table 1
Physico-mechanical properties of cement–rubber composite (CRC samples) [15]

Volume ratio of rubber particles (%)	w/c	Air-entrainment (%)	Fresh unit weight (kg/m^3)	Hardened dry unit weight (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)	Elasticity dynamic modulus (GPa)
0	0.30	2.0	2010	1910	82.0	3.4	25.0
10	0.32	5.0	1917	1752	49.7	3.8	18.5
20	0.35	8.7	1834	1649	40.2	4.2	15.3
30	0.39	11.8	1772	1473	23.3	4.0	12.0
40	0.44	14.0	1706	1297	16.0	3.8	9.5
50	0.52	17.0	1600	1150	10.5	3.2	6.2

means of geometrical measurement and weighing. The elasticity dynamic moduli were determined by applying longitudinal ultrasonic vibration, as specified in Standard NF P 18-418 [19]. The compressive and flexural tests were carried out in accordance with Standard EN 196-1 [20].

3. Results and discussion

Test results of fresh and 28 days-hardened ACRC material properties for all rubber volume ratios, are listed in Table 2. Each test result is the average of three test values.

3.1. Properties of fresh composite

3.1.1. Slump

The workability of the fresh ACRC material is significantly improved due to the generation of micro air-bubbles when an air-entraining agent is added. The effect of air-entrainment on the slump of a fresh aerated composite containing different rubber volume ratios is shown in Fig. 1. The slump as a measure of fluidity and consistency of material increases with air content. When no air-entraining agent was used, the slump of all the mixes was in order of 90–100 mm. For the ACRC containing 50% rubber particles if compared to the correspondent CRC, the slump improved to a value from 100 to 169.5 mm. Consequently, mixing water can be reduced so as to achieve constant workability (i.e. slump on the order of 90–100 mm). This reduction in water enhances the composite's mechanical properties. The plasticizer effect of proteinic air-entraining agent has been shown in previous study [21]. Results have indicated that this proteinic air-entraining acts both as plasticizer agent and an air-entraining promoter. Fig. 2 displays sample photograph images with the same magnification of both the CRC and ACRC fresh mix samples containing 50% of rubber particles. It should be noted that the

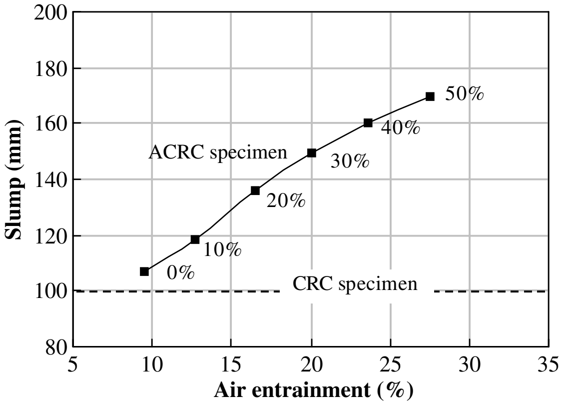

Fig. 1. Effect of air-entrainment on the slump of fresh composite containing different rubber volume ratios (0–50%).

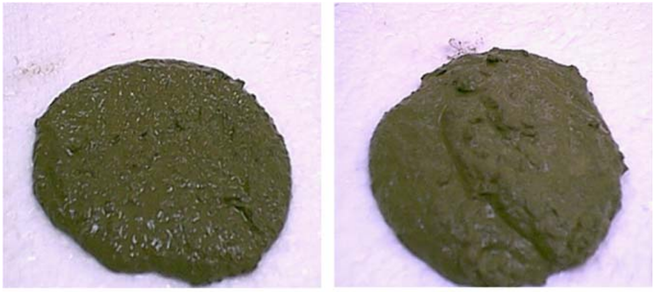
CRC 50%
ACRC 50%

Fig. 2. Sample photograph images of CRC and ACRC fresh specimens containing 50% of rubber particles.

Table 2
Physico-mechanical properties of aerated cement–rubber composite (ACRC samples)

Volume ratio of rubber particles (%)	w/c	Air-entrainment (%)	Fresh unit weight (kg/m^3)	Hardened dry unit weight (kg/m^3)	Compressive strength (MPa)	CLPA[a] (%)	Flexural strength (MPa)	Elasticity dynamic modulus (GPa)
0	0.30	9.5	1818	1530	36.2	5.8	3.2	14.0
10	0.32	12.7	1672	1314	23.5	4.2	3.0	11.5
20	0.35	16.5	1545	1173	16.3	3.6	2.7	8.5
30	0.39	20.0	1432	1090	11.0	2.6	2.4	7.5
40	0.44	23.6	1326	945	6.7	2.5	1.8	5.0
50	0.52	28.2	1160	785	3.8	2.3	1.4	3.7

[a] Compressive strength loss per air-entrainment.

composite aerated by adding a proteinic air-entraining agent gives rise to a foamed specimen. For 50% rubber particles, the fresh mix volume expanded by approximately 1.4 times compared to the CRC materials. The proteinic air-entraining acts as foaming agent, due probably to its chemical composition and emulsion properties. These observations are consistent with the measurements carried out, whose indicate an increase in the ratio of fresh unit weight of CRC sample to that of ACRC sample with increasing rubber content, for the same weigh of fresh mix (see Tables 1 and 2).

3.1.2. Air-entrainment

The results of air-entrainment measurements of ACRC composite, with respect to rubber particle volume, are displayed in Fig. 3. This figure clearly indicates that the addition of rubber particles in the cement matrix increases the level of air-entrainment. The values range between about 17.0% and 28.2%, respectively, for CRC and ACRC specimens with a 50% rubber volume ratio. For the cement paste, air-entrainment varied from 2.0% to 9.5%, in the same order. The higher air content in mixtures may be due to the capability of rubber particles to entrap air at their rough surface due to their non-polar nature. Similar observations were also made by several authors [11,13]. Reviewing paste literature on air-entrainment revealed that it is clearly an extremely complex process, which is affected by many factors, including the mixing process, material mixture proportioning, fine and coarse aggregates, physical and chemical properties of cement, water amount, dosage and properties of air-entraining agent and a range of other parameters [22]. The increase of water content during mixing also incites the entrapment of air. In order to verify these assumptions, air-entrainment measurements of ACRC samples containing 0%, 20% and 50% rubber by volume were performed while reducing water content during mixing. Test results have been summarized in Table 3. The reduction in mixing water content leads to a lower air-entrainment for cement pastes. However, the values of air-entrainment obtained are almost identical for each rubber particles content (20–50%). The improvement in air-entrainment was also independent of the dosage of the cement. The composite containing rubber particles as replacement to cement, exhibits a higher air-entrainment level than the cement paste. These results suggest that both the level of mixing water and the cement dosage are not the predominant parameters within the entrapped-air mechanism. The level of air-entrainment can be correlated with the morphology of rubber particles, emulsion property of proteinic agent and most likely with the phenomenon of air-entraining agent/cement/rubber interaction systems.

Table 3
Experimental results of air-entrainment at different water mixing of ACRC samples

w/c	Air-entrainment (%)		
	0% Rubber	20% Rubber	50% Rubber
0.26	6.3	–	–
0.30	9.5	15.8	–
0.35	–	16.5	–
0.47	–	–	28.7
0.52	–	–	28.2

3.2. Properties of hardened composites

3.2.1. Dry unit weight

The variation in dry unit weight vs. rubber particle content is shown in Fig. 4. This figure clearly indicates that the addition of rubber particles reduces the dry unit weight in a linear rate. Values decrease from 1910 kg/m^3 for cement paste to 1150 and 785 kg/m^3 for CRC and ACRC samples respectively containing 50% rubber particles. These values correspond to reduction of up to 40% and 59%, respectively. It should be noted that the decrease in dry unit weight of ACRC, derived by aerating the CRC sample, is regular regardless of rubber volume ratio and stems from the stability of the entrained air bubbles. However, air-bubbles in fresh material are inherently unstable. According to Myers works [23], three fundamental physical mechanisms may lead to the collapse of air-bubbles: (1) diffusion of air from a small bubble (higher internal pressure)

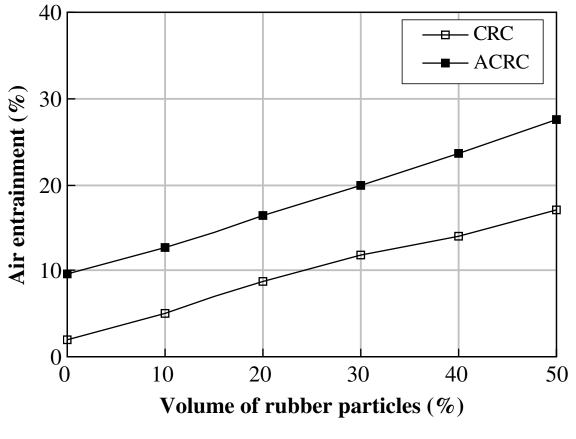

Fig. 3. Variation of air-entrainment with volume ratio of rubber particles.

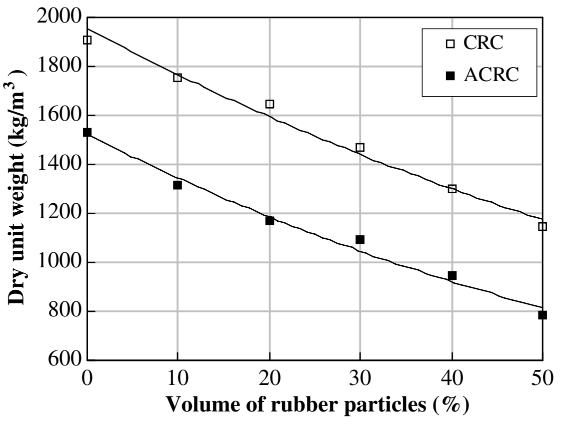

Fig. 4. Variation of dry unit weight of composites with volume ratio of rubber particles.

to a larger one (lower internal pressure), (2) bubble coalescence due to capillary flow leading to rupture of the interface between the dispersed air and the surrounding matrix, and (3) rapid hydrodynamic drainage of mix water between bubbles leading to rapid collapse. In addition, if specimen setting is severely retarded, lack of small air-bubbles may be expected. However, in this study, no measurements of air-entrainment in hardened specimen were carried out. The stability of air-bubbles was indirectly evaluated through the relationship between unit weight of the hardened ACRC sample and that of the fresh sample. Fig. 5 shows a linear variation and indicates that the entrained air-bubbles are stable. No reduction of the sample volume was observed when the material setting occurs.

3.2.2. Dynamic modulus of elasticity

Results in the form of dynamic modulus of elasticity of ACRC and CRC samples vs. rubber particle content are given in Fig. 6. This figure shows that for a 50% rubber volume ratio, the dynamic modulus of elasticity when aerating a composite decreases from approximately 6.2 to 3.7 GPa. It corresponds to reduction of 40.3%. Rubber however favors the absorption of ultrasonic waves. The values of the velocity of the ultrasonic wave, in both the rubber prior to shredding, and in the cement paste, are respectively of 175 and 3700 m/s. The value for rubber is over 21 times lower than that for cement paste. Consequently, we may assume that constriction of the dynamic modulus of elasticity in the composite is also due to the presence of discontinuous air-entrainment voids. The ultrasonic wave bypasses these voids in order to propagate within the cement matrix. Incorporation of rubber particles into the cement matrix reveals the ability of composites to both reduce sound intensity and dampen vibrations, which serves to provide a high level of sound insulation.

3.2.3. Compressive strength

Results of 28 days-compressive strength vs. rubber volume particles are given in Fig. 7. The increase of the rubber content serves to considerably decrease compressive strength. Values amount to about 10.5 and 3.8 MPa for CRC and ACRC specimens, respectively, both them containing 50% rubber particles by volume. Although the strength was reduced, the composite satisfies the basic requirement of construction materials, and could be used for load-bearing wall, according to the RILEM functional classification [24].

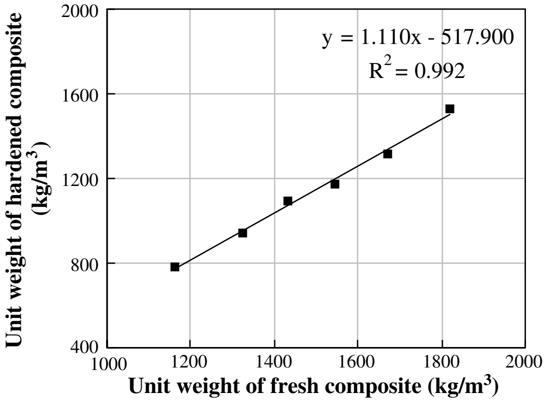

Fig. 5. Relationship between unit weight of fresh and hardened composite.

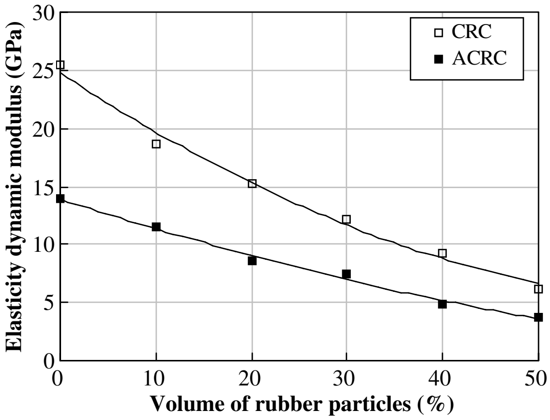

Fig. 6. Variation of elasticity dynamic modulus with volume ratio of rubber particles.

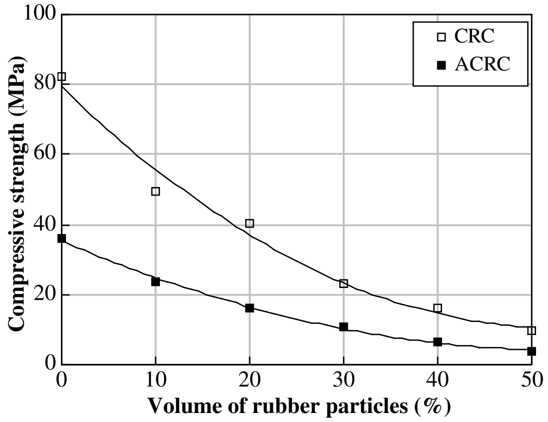

Fig. 7. Variation of compressive strength with volume ratio of rubber particles.

The effect of adding air-entraining agent on the mechanical behavior of the composite has been investigated by evaluating the compressive strength loss per air-entrainment (CLPA). The compressive strength loss between CRC and ACRC samples for a given rubber volume, per air entrainment is given by Eq. (1):

$$\mathrm{CLPA}\ (\%) = \frac{(R_{\mathrm{c(CRC)}} - R_{\mathrm{c(ACRC)}})/R_{\mathrm{c(CRC)}}}{P_{\mathrm{(ACRC)}}} \tag{1}$$

where $R_{\mathrm{c(CRC)}}$ and $R_{\mathrm{c(ACRC)}}$ are respectively the compressive strength of CRC and ACRC samples, $P_{\mathrm{(ACRC)}}$ is the air-entrainment.

The calculated vales of the 28-days CLPA of aerated composite are listed in Table 2. For aerated concretes, the CLPA typically lies in the range of approximately 4–6% [24]. Results on the effect of air-entrainment on the

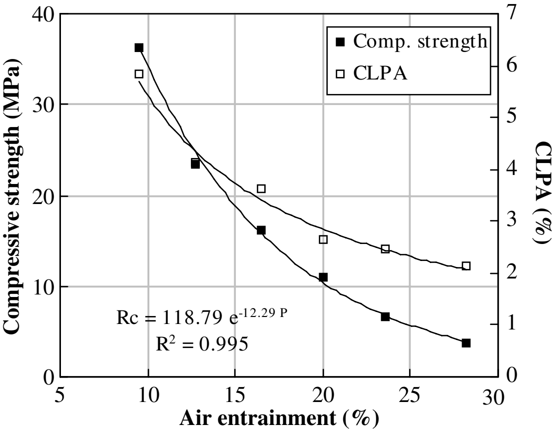

Fig. 8. Relationship between air-entrainment-compressive strength, and air-entrainment-CLPA.

28-day CLPA of ACRC specimen are displayed in Fig. 8. It is indicated that values decrease from 5.8% to 2.2% for samples containing rubber volume ratio ranged from 0 to 50%. It should be observed that this CLPA is lower than that for aerated concrete. Although the increase in air-entrainment, the CLPA decreases. These results highlight the effect of the proteinic air-entraining agent on the cement matrix/rubber interaction system, as regards the mechanical strength of the composite.

Fig. 9 presents a relationship between compressive strength and composite dry unit weight. It is evident that a decrease in unit weight $\rho = (\text{kg/m}^3)$ induces a reduction in compressive strength R_c (MPa). The following empirical relationships have been proposed: $R_c = 0.0423 \exp(0.0027\rho)$ and $R_c = 0.0365 \exp(0.0031\rho)$ (yielding correlation coefficients of $R^2 = 0.99$ and $R^2 = 0.98$), for ACRC and CRC samples respectively. Moreover, Fig. 9 indicates that for the same dry unit weight, the ACRC sample exhibits a higher compressive strength than the CRC sample. For the same dry unit weight, the ACRC sample exhibits the lower w/c ratios. These results are similar to those obtained by Ruzicka [5] on the properties of aerated clayey-concrete produced using a proteinic aerating agent. The proteinic aerating agent is likely to be responsible for the additional particles being bound in the matrix. The work conducted by Yang et al. [25] pertains to the effect of a new type of saponin air-entraining agent on concrete properties. Results have shown that for air content of 7%, the aerated concrete displayed a higher compressive strength than a traditional concrete, for 2% air content. According to Becher's research [26], when a globular molecule, as applicable to the present case, is placed into an aqueous solution, it diffuses towards the liquid-air interface. Submitted to the action of interfacial water molecules, the intramolecular binding breaks and incites a micro-unfolding of the structure. The partially unrolled protein is then hydrated and activated; it becomes very unstable due to the presence of many hydrophilic arrangements. By means of unfolding and stretching the protein at the interface, both the hydrophilic and hydrophobic residues are once again left in the aqueous and non-aqueous phases respectively. The protein adsorbed in this manner forms a resistant barrier at the interface that counters both the diffusion of air-entrainment and the tendency to coalesce into bubbles. In addition, interactions near the interface are influenced by the nature of the chemical specimens present in the cementitious medium. The influence of SiO_3^{2-} and Na^+ ions on the toughness of aerated clayey-concrete has also been investigated [5].

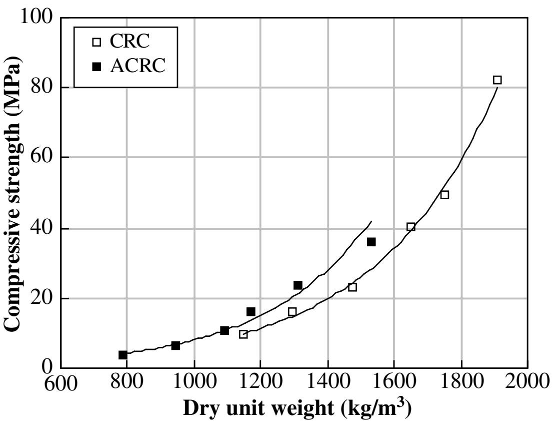

Fig. 9. Relationship between dry unit weight and compressive strength.

The compressive strength of the ACRC samples can be improved by reducing total mixing water in order to achieve a constant workability, such as that of CRC. We have previously observed that air-entrainment serves to significantly raise the level of workability.

The compressive strength of the material is influenced by several factors, i.e., state of the microcrystalline gel in the cement matrix, type of aggregate, the cement paste/aggregate interfacial zone, and, in particular, porosity (gel pores, capillary pores and entrained air). A number of functions have been proposed by several authors to express this strength-porosity relationship. The relationship between air entrainment and compressive strength of the ACRC sample is shown in Fig. 8. From this graph, it can be seen that the strength-air entrainment equation fitted using an exponential function, as stipulated by Ryshkecvitch [27], best explains the relation and yields the following expression: $R_c = R_c^0 \exp(-lP)$. In this equation, R_c and R_c^0 represent the compressive strength and theoretical compressive strength of the sample at zero air-entrainment, l is an empirical parameter related to the type of material, and P is the air-entrainment. In our case, the derived values of R_c^0 and l are 118.79 MPa and 12.29 respectively, with a high correlation coefficient of $R^2 = 0.995$. It is interesting to note that the value of l nearly lies within the range cited by Rôbler and Odler [28] for foamed concrete.

3.2.4. Flexural strength

The variation in 28-day flexural strength as a function of rubber volume content is shown in Fig. 10. The composite's behavior has been completely modified due to a change in porous structure system within the matrix. A

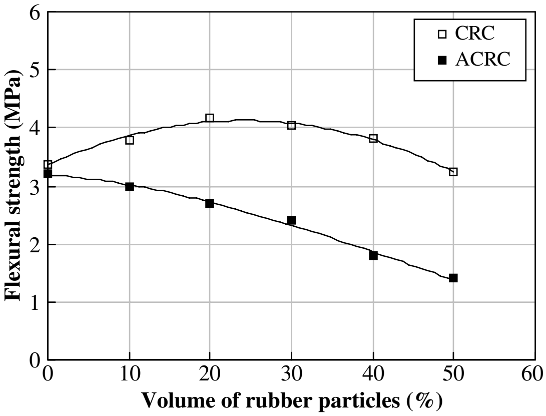

Fig. 10. Variation of flexural strength with volume content of rubber particles.

reduction in the flexural strength of the ACRC sample is observed. Value decreases from 3.3 to 1.4 MPa. This finding suggests that the sample's porous structure predominates over the effect of rubber aggregate elasticity, due to the entrapped air effect. Results also indicated that for a given rubber volume ratio, the decrease in flexural strength of ACRC sample is lower than that in compressive strength, probably due to the effect of polypropylene fibers. The reduction in mixing water for the purpose of achieving constant workability (i.e. slump on the order of 90–100 mm) may also serve to enhance the mechanical properties. For CRC sample, the curves reveal maxima at a volume ratio of between 20% and 30% of rubber content, as a result of both the nature of the elasticity and the non-brittle characteristic under loading of the rubber.

4. Conclusions

The work presented herein has focused on the effect of a proteinic air-entraining agent on the physico-mechanical properties of cement composite containing various volume ratios of rubber particles. The tests conducted on fresh composite properties have shown that workability is significantly improved due to the generation of air bubbles when air-entraining agent is added. Slump is enhanced as well. The addition of rubber particles favors air-entrainment due to both their texture and greater specific area. A study carried out on hardened material properties concluded that the aerated composite reached a dry unit weight of about 780 kg/m^3 with a compressive strength of 3.8 MPa. The reduction in flexural strength is lower than that in compressive strength. Although the strength was reduced, the composite satisfies the basic requirement for load-bearing wall. The presence of air voids and rubber particles in the matrix reduces the elasticity dynamic modulus, which indicates a high level of sound insulation of the composite. Results also highlighted the effect of adding a proteinic air-entraining agent on binding air-entraining agent/cement/rubber particles. For the same dry unit weight, the ACRC samlpe exhibits a higher compressive strength than CRC sample, due to the lower w/c ratios. The potential for development, therefore, seems to be very promising.

This research has demonstrated the potential of aerated cement-rubber composites in attaining substantial physico-mechanical properties and allows considering a broad range of applications in the field of cellular concrete. It would be valuable to investigate the thermal and hydraulic transport properties of the aerated composite.

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