Innovative Infrastructure Solutions (2023) 8:290
https://doi.org/10.1007/s41062-023-01258-8

TECHNICAL PAPER

Mechanical behavior of reinforced concrete hybrid beams made with normal concrete, foamed cellular concrete and fiber reinforced foamed cellular concrete

Facundo Atuel Retamal[1] · Viviana Carolina Rougier[1]

Received: 1 September 2022 / Accepted: 20 September 2023 / Published online: 13 October 2023

Abstract

Cellular concrete has increased in popularity in the construction industry due to its particular characteristics. It is classified as lightweight concrete and its structural behavior is consistent with this definition, showing less rigidity and more brittleness compared to normal concrete. In this work, experimental results obtained through bending tests on hybrid beams formed by two layers, one of normal concrete and the other of foamed cellular concrete, reinforced with polypropylene fibers, are presented. In this way, it was sought to increase the rigidity of the elements subjected to bending, through the incorporation of the normal density concrete layer and, in addition, to reduce the fragility of the foamed cellular concrete, through the addition of polypropylene fibers. Furthermore, the interface between both layers was treated with chemical glue for concrete, to achieve a better structural behavior of the elements. Characterization of the materials used was also carried out. In this way, the mechanical properties of the different concrete are analyzed and compared and the bending behavior of the hybrid beams is evaluated. Conclusions are drowned

Keywords Foamed cellular concrete · Hybrid Beams · Polypropylene Fibers · Interface Treatment · Experimental Campaign

Introduction

Reinforced concrete is a widely used construction material in the world and its applications are numerous and varied (Lee, Lim, Lim, and Tan, 2018). Due to technological advances and architectural challenges, the need to develop new types of concrete and also innovative structural solutions are created. Thus, the interest in structurally using special concretes arises, which are concretes prepared for specific uses or purposes. Among them, light concrete and fiber reinforced concrete can be mentioned (Hardjasaputra, Ng, Urgessa, Lesmana, and Sidharta, 2017). Cellular concrete (CC) is a type of lightweight concrete that is composed of a cement base mix into which uniformly distributed air or gas bubbles are incorporated, which give the material a porous structure [1]. There are various types of CC, one type of classification of them is carried out according to the procedure of incorporating air or gas into the mixture [2]. Among these, foamed cellular concrete (FCC) is one in which air is added to a mortar or cement paste, through a preformed foam, which is generated with a foaming agent diluted in water and compressed air (A.C.I., 2014). It is also common to incorporate active and/or inert mineral additions, chemical additives, fibers, and others (Ramamurthy, Nambiar, and Ranjani, 2009).With densities between 300 and 2000 kg/m^3, CC is classified as lightweight concrete (LWC) and its structural behavior is following this assumption [3]. Compared to normal concrete (NC), FCC has less rigidity and more brittleness [4], as is usual in LWC. However, structural use of CC and FCC is increasing, and so, investigations are being carried out [5–7],Tam, Lim, Sri Ravindrarajah,

Facundo Atuel Retamal and Viviana Carolina Rougier contributed equally to this work.

✉ Facundo Atuel Retamal
retamalf@frcu.utn.edu.ar

Viviana Carolina Rougier
rougierv@frcu.utn.edu.ar

[1] Computational Mechanics and Structures Research Group (GIMCE), Civil Engineering Department, Concepcio´N del Uruguay Regional Faculty (FRCU), National Technological University (UTN), Ing. Pereyra 676, E3264 Concepción del Uruguay, Entre Ríos, Argentina

and Lee, 1987). Jones and McCarthy [4], through a laboratory study evaluated FCC with the addition of two types of fly ash on their potential for use in structural applications. They also added polypropylene fibers to enhance plasticity and tensile strength. They concluded that FCC is viable for structural uses. In spite of that, the material's particular characteristics, especially high drying shrinkage strain and relatively low tensile strength and stiffness performance imply that the direct substitution of the NC is not recommended, and more innovative structural forms should be developed. Dawood and Hamad [8], studied FCC's fresh and hardened properties, and focuses on the addition of fibers to the mixes. Two types of fibers were added, polypropylene fibers (PPF), glass fibers (GF), and the combination of both to obtain hybrid fibers (GF+PPF). This work also focuses on the effect of hybrid fibers on the flexural toughness of the material. They observed that the PPF denotes higher efficiency in the flexural toughness than GF. The flexural toughness increased with the volume of the fibers added. The hybridization shows the best flexural toughness values due to the cooperative work of the combined fibers (PPF+GF), which boosts the performance of flexural toughness in pre-crack and post-crack zones. Afifuddin, Churrany, et al. (2017), studied the shear behavior of fiber foam reinforced concrete (FFRC) beams and they compared the results with controls specimens made of NC. All the tested specimens present shear failure mode and show larger load capacity and lesser deflection than the theoretical analysis. They also observed lesser rigidity in the FFRC specimens than in the NC control ones, but the ductility was larger

in the first ones, probably as a result of the fiber content. Lee et al. [9], studied the flexural behavior of foamed mortar (FM) beams and slabs. They worked with densities between 1700 and 1800 kg/m^3, and showed that those elements performed successfully, but with ultimate loads about 8 to 34% lower in the case of beams, and 18% in slabs. They also observed, that the FM elements were weak in resisting shear forces and have lesser rigidity than the NC control specimens.

On the other hand, the growing demand for optimization of structural systems has led to the investigation of new alternatives in the combination of materials and possibilities of their application. These combinations depend on the objective: improve load capacity, achieve greater sustainability, and reduce its weight, among others. Structures designed in this way are called hybrid structures or elements. Therefore, the study of interaction, proper combination, and joints between different materials is very important to make the best advantage of their different inherent qualities [10]. Holschemacher, Iskhakov, Ribakov, and Mueller (2012), developed two-layered beams made of fiber-reinforced high-strength concrete (FRHSC) in the compressed zone and NC, without fibers, in the tensile one. They prepared and carried out an experimental program based on a theoretical result of design and, this way, showed that with the optimum fiber dosage, beams had a higher Poisson coefficient, more energy dissipation, and consequently, a higher ductility. They also proposed that this kind of structural element, the HSC should be cast before the NC. Later on, Holschemacher, Iqbal, Ali, and Bier [11], carried out studies on the strengthening of structural elements, where they used fiber-reinforced lightweight self-compacting concrete (FRLSCC). The results showed a significant increase in the absorption capacity of the bending moment. Holschemacher *et al.* have done other relevant publications following their studies on the combination of materials on layered structural elements [12], Iskhakov, Ribakov, and Holschemacher, 2017; [13]. After that, they studied full-scale prestressed two-layer reinforced concrete beams (PTLB) in four points bending tests, showing the efficiency of such structural elements. No debonding between the component materials was observed and their practical application shows effectiveness and economy in bending elements [14]. Nes and Øverli [10], studied the bending and shear behavior of hybrid beams composed of NC on the top face and fiber-reinforced lightweight concrete (FRLWC) on the bottom, with 0.5% 1.0% of steel fibers. They found that the fibers had a considerable influence on the performance of the FRLWC and hybrid beams had no problems with the bond between the layers of concrete. They were able to reach a reduction in the self-weight of the structural elements with promising results and good premises for increasing efficiency in buildings.Iskhakov and Ribakov [15], worked with structural elements composed of a combination of fiber-reinforced high strength concrete (FRHSC) and NC, which behaved satisfactorily. Studies on different aspects of hybrid composite-concrete beams were carried out: flexural strength (De Sutter, Verbruggen, De Munck, and Tysmans, 2016), shear behavior (De Sutter, Verbruggen, and Tysmans, 2016a), [16], application to the materialization of floors systems [17], fracture behavior [18], achieving satisfactory results in all cases. Karthik and Maruthachalam [19] research on hybrid beams made up of concrete reinforced with different types of fibers, regarding their shear behavior. Usman and Hussin [20], evaluated a type of hybrid beam where the LWC is located in an arc located inside the reinforced concrete beam, and studied its bending behavior in comparison with a standard NC beam. They obtained very similar results between the two types of specimens.

In this work, continuing the line of research of a previously published article (Retamal, Rougier, and Escalante, 2020), an experimental campaign has been conducted to study the structural behavior of hybrid reinforced concrete beams made of FCC reinforced with polypropylene fibers on the bottom layer and NC, without the addition of fibers, in the top. Different volumes of fiber reinforcement were evaluated: 0%, 0.5%, and 1.0% in volume, and the interface was tested with and without treatment. For the first case, a commercial chemical bond was placed before the top layer cast. Experimental characterization of the materials was also carried out, also for the treated and non-treated interfaces. The obtained results show that the PPF decreases the brittleness and fragility of the FCC. Also, shear behavior was improved with PPF inclusion. On the other hand, the NC upper layer increases the structural element rigidity. No de-bonding issues were observed since this phenomenon occurred always after the yield load of the beams. However, the treated interface showed a better behavior, since they don't show interface displacement or failure even for high yield strain. The results on hybrid beams were compared with those obtained for a control beam made of NC, showing a better structural behavior in addition to the expected self-weight decrease.

Materials and methods

The materials used to prepare the cement paste base mix for the FCC were composite Portland Cement (CPC 50), with a specific density equal to 2.954, experimentally determined according to ASTM C188 [21],fine river sand, with a specific density in a saturated dry surface condition equal to 2.65, obtained according to ASTM C128 [22] and drinking water. To prepare the pre-formed foam, a commercial brand synthetic type of foaming agent, available in the local market, was used. For the NC mix, the same materials were used, except for the pre-formed foam, and the addition of coarse aggregate. This last, had a specific density equal to 2.63, experimentally determined according to ASTM C127 [23]. The PPF used were from a commercial brand (MACRONITA® 0,6), which are synthetic fibers cut from polymeric materials. With lengths equal to 50 mm, 0.60 mm diameter; slenderness or aspect ratio (AR) equal to 83; 920 kg/m^3 of density; elasticity modulus of 6 GPa and tensile strength of 548 MPa. In table 1, materials mix designs are presented.

Table 1 Materials mix designs

Material	FCC	FRFCC–0.5	FRFCC–1.0	NC
Cement [kg/m^3]	1049	1049	1049	390
Sand [kg/m^3]	500	500	500	734
Coarse ag. [kg/m^3]	–	–	–	1019
Water [kg/m^3]	350	350	350	195
Foam [kg/m^3]	5.25	5.25	5.25	–
Plastizicer [kg/m^3]	–	–	–	4.68
Fibers [%]	–	0.50	1.00	–

Materials characterization

Tests carried out in order to characterize the used materials are described in this section. The consistency of the materials was studied with the slump test, according to ASTM C143 [24], and also with the slump flow test for the FCCs, following ASTM C1611 [25]. This way, the high flowability of this material, could be studied. Flow time was not considered, because this phenomenon occurs almost immediately after lifting the Abrams cone (Fig. 1).

Simple compression tests were also done on FCC, FRFCC-0.5, FRFCC-1.0, and NC, according to ASTM C39 Standard [26]. The curing time for the FCCs was extended up to 56 days because its development of mechanical strength requires more time compared to NC [4]. For studying the behavior of the materials in compression, load–deflection curves of these specimens were obtained. It was done using potentiometers and a load cell, as can be seen in Fig. 2. An HBM QuantumX MX840B unit was used, connected to a computer with CatmanEasy software, for continuous data measurement.

Used mix designs of FRFCC were tested in 3-point-bending tests, performed as specified by Rilem TC 162-TDF (Vandewalle, Nemegeer, Balazs, and Di Prisco, 2002). This way, the influence of the PPF addition on the structural behavior of FCC could be observed. Test setup is presented in Fig. 3. The continuous load-deflection equipment was also used on these beams.

The interface bonding was also studied, applying the Bi Surface Shear Test (BSST) which was originally developed for evaluating the bond strength between new and existing concrete subjected to shear stress [27].

Hybrid beams

In this work, 10 reinforced concrete beams were fabricated and tested under four-point bending. A total of 6 beams,

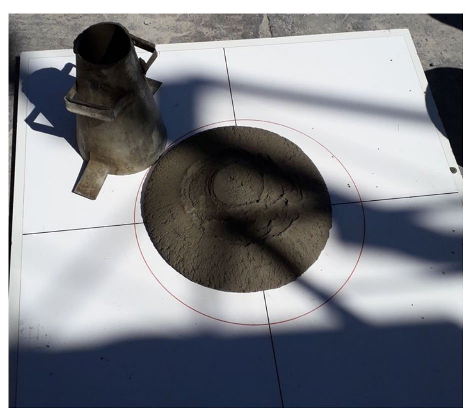


Fig. 1 Slump flow test

Fig. 2 Simple compression test setup

Fig. 3 Bending test for evaluating the tensile behavior of fiber reinforced concrete

named hybrid beams, were built with NC and FCC in the top and bottom layers respectively. The two parameters studied in the aforementioned specimens were the interface treatment and the fiber content in the FCC. In Table 2a summary of each beam (B-1/2/3), hybrid beam with a treated interface (HB-1/2/3-TI), hybrid beams without interface treatment (HB-1/2/3-UI), and control beam (CB) is presented. The numbers 1, 2 and 3, correspond to fiber dosage

Table 2 Summary of beams, hybrid beams and control beam

No	Beam	Component meterial	interface
1	HB-1-UI	NC (top layer) FCC (bottom layer)	Untreated
2	HB-1-TI	NC (top layer) FCC (bottom layer)	Treated
3	HB-2-UI	NC (top layer) FRFCC-0.5 (bottom layer)	Untreated
4	HB-2-TI	NC (top layer) FRFCC-0.5 (bottom layer)	Treated
5	HB-3-UI	NC (top layer) FRFCC-0.1 (bottom layer)	Untreated
6	HB-3-TI	NC (top layer) FRFCC-0.1 (bottom layer)	Treated
7	B-1	FCC (entire beam)	No interface
8	B-2	FRFCC-0.5 (entire beam)	No interface
9	B-3	FRFCC-0.1 (entire beam)	No interface
10	CB	NC (entire beam)	No interface

on each FCC mix used, 0.0%, 0.5%, and 1.0% by volume, respectively. In 3 of these hybrid beams (HB-1/2/3-TI), the interface between NC and FCC/FRFCC-0.5/FRFCC-1.0 was treated with a chemical commercial concrete bond (Sikadur 32 Gel) and, on the other 3 (HB-1/2/3-UI), the interface doesn't receive any special treatment. At the FCC bottom layer, the dosage of fibers was 0.0%, 0.5%, and 1.0% by volume. Also, 3 beams were made entirely with FCC with 0.0%, 0.5%, and 1.0% by volume of PPF addition, were cast (B-1/2/3). Finally, an NC control beam was made (CB). The longitudinal reinforcement bars were made of commercial steel of 6 mm diameter, 2 at the bottom layer, and 2 at the top layer. For the stirrups, the same type and diameter were used, with 100 mm of separation between each one.

The geometric characteristics of beams used in the experimental campaigns were: sections 80 mm wide and 160 mm high, with a total length of 1,100 mm. They were over-reinforced in shear, to minimize the effect of this effort. For the hybrid beams, a thickness of the upper compression layer of 8 mm of NC and the same thickness of the lower layer, made up of FCC/FRFCC-0.5/FRFFC-1.0, were adopted in each case. This characteristics are presented in Fig. 4.

A schematic representation of the four-point bending test configuration is presented in Fig. 5. The test was performed according to ASTM C78. The beam supports consisted of roller support at the two ends. The outer loading span was 1100 mm and the inner loading span was 1000 mm.

In Fig. 6, hybrid beams test setup is shown.The load was applied using a universal testing machine with a capacity of 1000 kN and a loading control rate of 0.20 mm/min. A potentiometer, placed at the bottom of the beam in a vertical position, was used to record the midspan deflection. The data were collected by a continuous

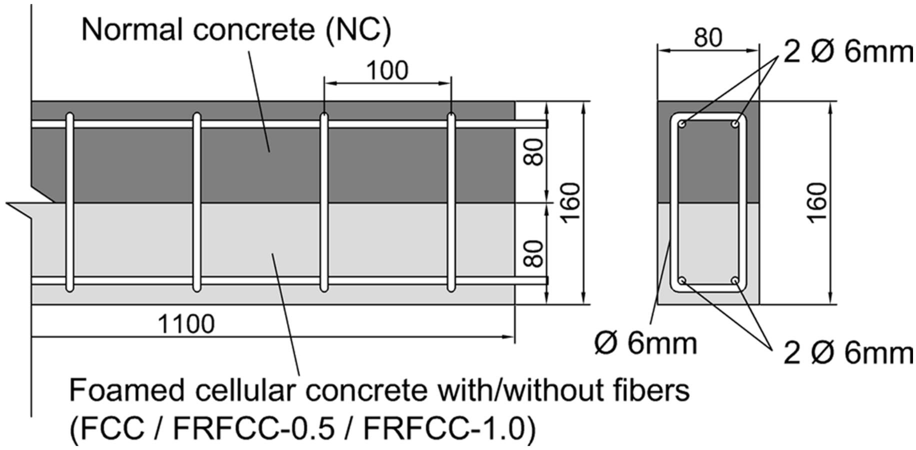


Fig. 4 Geometric characteristics and reinforcement details of beams

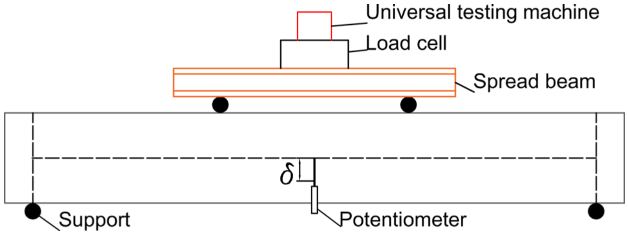


Fig. 5 Beams flexural test setup

Fig. 6 Hybrid beam test set up

load-deflection measurement equipment system and they were analyzed to obtain the load-deflection curves.

Results and discussion

This section is ordered following the structure of the previous one (2), in the first place, the material characterization and then, studied beams are summarized.

Table 3 Experimental results for the characterization of different types of concrete used

Material	FCC	FRFCC–0.5	FRFCC–1.0	NC
Density [kg/m]	1 469	1 504	1 446	2 330
Slump [cm]	25.80	24.10	20.80	18.70
Slump Flow [cm]	40.20	36.50	33.10	–
Compressive strength [MPa]	14.57	14.12	14.02	35.17
Tensile strength [MPa]	1.57	1.71	1.52	2.93
fR,CMOD1[MPa]	–	0.56	0.75	–
fR,CMOD2[MPa]	–	0.38	0.82	–
fR,CMOD3[MPa]	–	0.37	0.84	–
fR,CMOD4[MPa]	–	0.34	0.81	–
Bond strength (UI) [MPa]	1.07	1.71	1.47	–
Bond strength (TI) [MPa]	1.55	2.00	2.18	–

Materials characterization

The mean values of the test results for characterizing the different types of concretes used are presented in Table 3. There, materials density; slump test; slump flow test; compressive strength; tensile strength; residual tensile strength ($f_{R,CMOD1}$, $f_{R,CMOD2}$, $f_{R,CMOD3}$, $f_{R,CMOD4}$) for corresponding crack mouth opening displacement (CMOD); and bond strength of untreated interface (UI) and treated interface (TI)are summarized.

It can be seen that the density, compression strength, and tensile strength were very similar in each of the FCCs mixes, which was expected, because the same mix design was used in the 3 cases, except for the amount of fiber addition. The mid density of the 3 types of FCCs was 1 473 kg/m3 and for the NC was 2 330 kg/m3. Then, an average reduction of 36.78 % in density was obtained for FCCs in comparison with NC.

The 3 mixes of FCC and NC had an important flowability, not being self-compacting none of them, and it was

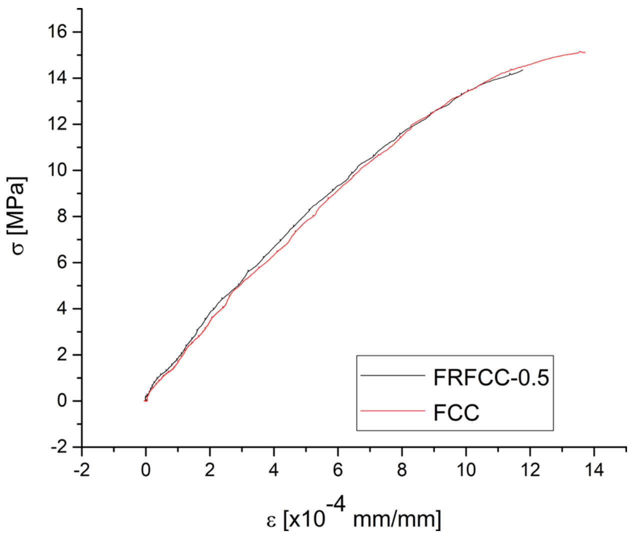


Fig. 7 Simple compression test curves for FCC and FRFCC-0.5

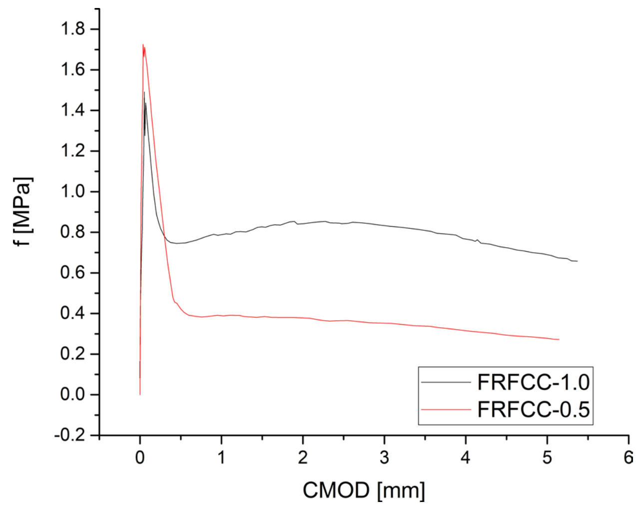


Fig. 8 Bending test tension-CMOD curves for FRFCC-0.5 and FRFCC-1.0

appreciable the flow reduction with the addition of fibers. Slump flow wasn't considered in the case of NC, for not being a self-leveling or high spread ratio material.

Examples of stress-strain curves up to the peak, determined through a simple compression test, for 2 samples of FCC, with and without fibers, are presented in Fig. 7 By them, it was observed that the number of fibers doesn't affect the compressive behavior of the material at the pre-peak stage, as happens with fiber-reinforced normal concrete (FRNC) [28].

These curves also exposed the behavior of FCC as a typical LWC, as shown in different studies [1], with a lower modulus of elasticity than NC and, this way, lesser rigidity. Mid compression strength for the 3 FCCs was 14.24 MPa, and 35.17 MPa for NC. Therefore, the mid compression strength of FFCs resulted in about 40.49% lesser than the NC value

Load-deflection curves were obtained by performing flexural tests, as was detailed previously, for evaluating the fiber-reinforced materials. Two examples of them are presented in Fig. 8. In this way, the effect of the number of fibers over the residual tensile strength for each specimen was revealed, showing the effectiveness of polypropylene fibers (PPF) applied to FCC. This results coincide with the observations of Jhatial et al. [29], who worked with mixes of lesser density and compression strength.

As it was told in section 2.1, the interface was characterized by performing a bi surface shear test. In Fig. 9, relevant aspects of this procedure are shown. In subsection a), a tested specimen where the test setup can be also seen. Failure, in most cases, occurs in the mass of FCCs or leaving rests of this material attached to the NC surface. This shows the development of bond strength, even for untreated interfaces.

Fibers across sections improve this adherence and also prevent the materials' total separation.

In Fig. 9b interface of two pieces of specimenare shown and rests of FCC in the treatement interface can be observed. In all cases TI generates failure to occur totally in the mass of FCCs, with no failure at the chemical bonding product. Also in Fig. 9, subsection c), bond shear strength is plotted against the number of fibers counted in crack of each specimen. Over the zero value of the x-axis the mixes without fibers are set. The rest of them are coincident with their respective fibers-across-section counted values. There's also distinctive symbology for treated (TI) and untreated (UT) interface, as well as for each of the materials evaluated. It can be seen that the number of fibers across the cross section of the crack failure has an important effect on the interface strength, showing larger shear strength with the increment of the number of fibers. The interface treatment also improves interface shear behavior, for every used mix design.

Hybrid beams

In Table 4, four-point flexural test results, performed on each beam according to ASTM C78, are presented. Maximum load at the entire load-deflection curve, weight of each beam, weight reduction percentage vs CB, and failure mode are summarized.

In Fig. 10, some examples of failure modes are presented. In Fig. 10a, shear failure on beam HB-1-UI is shown; on Fig. 10b, shear-flexural failure on beam HB-1-TI and on Fig. 10c, flexural failure on beam HB-2-TI are presented. Also, on Fig. 10d, flexural failure on CB is presented.

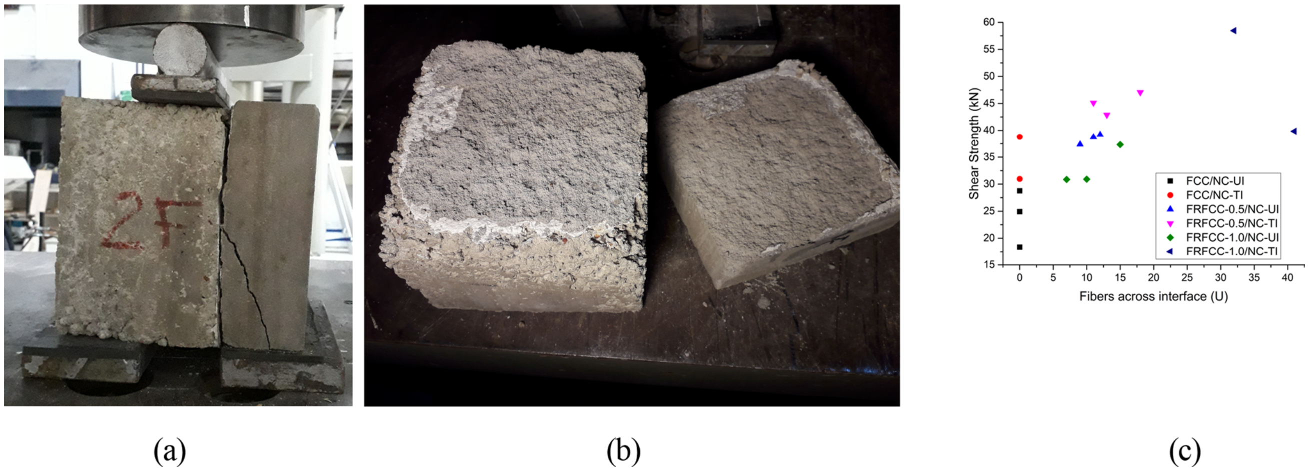


Fig. 9 Bi Surface Shear Test: **a** tested specimen, **b** treated interface failure and, **c** graphic of interface shear strength vs. fibers across the interface

Table 4 Four-point bending tests results

Beam	MaX [kN]	Weight [kg]	Weight reduction [%]	Failure moded
HB-1-UI	27.94	29.75	13.01	Shear
HB-1-TI	27.31	29.70	13.16	Shear-flexural
HB-2-UI	26.17	29.75	13.01	Flexural
HB-2-TI	29.08	29.90	12.57	Flexural
HB-3-UI	29.77	29.85	12.72	Flexural
HB-3-TI	29.54	29.80	12.87	Flexural
B-1	20.10	23.05	32.60	Shear
B-2	23.95	23.10	32.46	Flexural-shear
B-3	24.23	23.30	31.87	Flexural
CB	26.14	34.20		Flexural

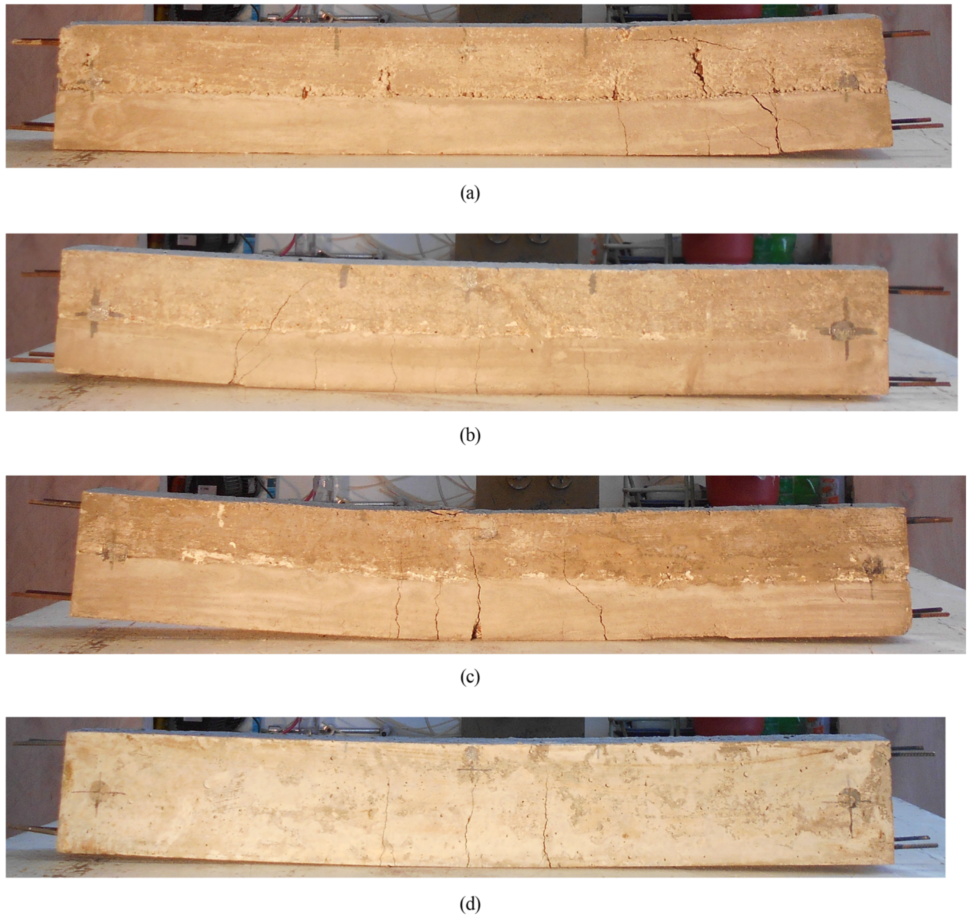
A two-way analysis is conducted below, on the beams test results. First, different types of beams for the same FCC are compared. Secondly, the same types of beams made of different FCCs are contrasted. This way, the effect of the different configurations is considered and exposed.

For the first case, the analysis is based on the study of the results as presented in Fig. 11. There, every type of beam: hole beams (B-1, B-2, B-3), hybrid beams with no treatment at the interface (HB-1-UI, HB-2-UI, HB-3-UI), and hybrid beams with interface treatment (HB-1-TI, HB-2-TI, HB-3-TI), made with the same type of FCC are compared with NC control beam (CB). Thus, the effect of the combined concretes and the interface treatment are analyzed.

In Fig. 11a different configuration beams made with FCC mix design, without fibers, are presented together and compared with the NC control beam. Hole FCC beam (B1), hybrid FCC-NC beam without interface treatment (HB-1-UI), and hybrid FCC-NC beam with treated interface (HB-1-UI) and NC control beam (CB) can be seen together. In subsection b) the same comparison, but for beams made with FRFCC-0.5, and in c) with FRFCC-1.0 is shown. This way, it is possible to observe that beams casted entirely with FCC have greater deformation at flexure than NC control beam, as was observed by Lee et al. [9], who worked with FCC of compression strength between 25 and 27 MPa. The same happens for the 3 FCC mix design but, with the addition of fibers, the HB curves tend to get closer to CB one, showing lesser deformation with the increment amount of fibers added. Observing this aspect of the HBs flexural response, their curves are approximately the same that CB for the ones with UI. And for those with TI, they are even upper, that is, lesser deflection than CB. The hybridization gets the deflection of the beams to be lesser than that of beams made entirely with FCC. Also, with the interface treatment, deformation reduces compared with beams made of NC (CB). Analyzing the maximum load of the different beam configurations a similar situation is observed. The hybridization of the beams enhances their behavior, getting upper load resistance.

The maximum loads are reached for the HB with TI, for all the FCCs used mixes. There is also notable, that the beams made entirely of FCC have a lesser top load than de CB, but with the addition of fibers, the beams B-2 and B-3 were able to reach the same values as the CBs. The addition of fibers to these beams, no hybrids, reduces their shear failure notably. The reduction of failure peaks, in every specimen curve for B-1 to B-2 and B-3, can also be observed. No brittle failure was observed on tested beams. Although some of them present important shear cracking. The UI ones were successful even in this aspect, but in the final stages of tests, they tend to present more erratic behavior. With the TI this aleatory performance was totally dismissed. Although, their response (UI) was satisfactory even for larger deflections.

Fig. 10 Examples of tested beams: **a** HB-1-TI, with shear failure; **b**



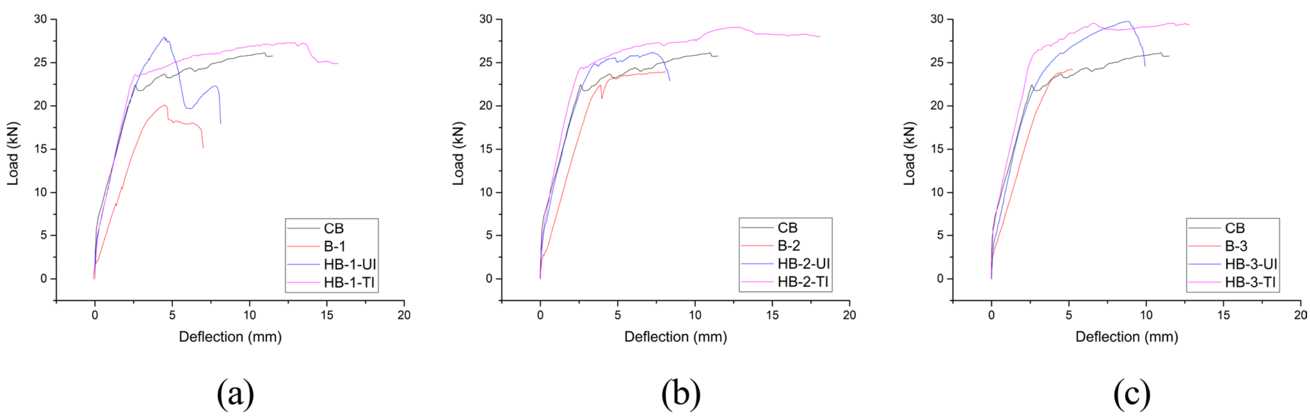


Fig. 11 Comparison of different types of beams bending test results: **a** Different configuration beams made with FCC mix design, **b** different configuration beams made with FRFCC-0.5 mix design and, **c** different configuration beams made with FRFCC-1.0

In Fig. 12, the same configuration beams made with FCC with different amounts of fibers are compared. In Fig. 12a flexural behavior curves of beams made entirely of the different FCCs (no hybrids) are superposed. There can be seen, the reduction in the failure peak previous to the yielding, with the addition of PP fibers and also the increment of the rigidity and maximum load that their addition generates. In Fig. 12b, hybrid beams made with FCCs with different amounts of PP fibers, without interface treatment, are shown. The behavior of UI specimens was equal up to the yielding step, which implies a satisfactory interface bond between the materials of both layers. After this point, the response of these structural elements turns to be erratic, principally because of the interface bonding behavior,

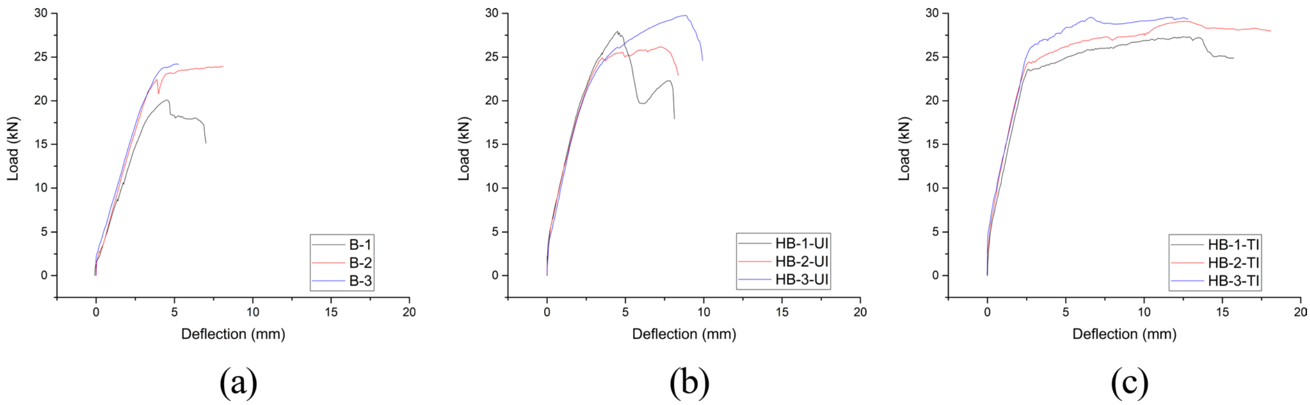


Fig. 12 Comparison of same type of beams made with different amount of PP fibers addition: **a** Beams made entirely of the same FCC, **b** hybrid beams with no treatment at the interface, and **c** hydrid beams with treated interface

which is in line with the results observed in the bi surface shear tests. Interface chemical treatment totally dismisses this erratic yielding behavior of the hybrid beams, as it can be seen in Fig. 12c, where the hybrid beams with a treated interface made of FCCs with different amounts of PP fibers are plotted together.

Conclusions

In this work, the flexural behavior of hybrid beams, composed of 2 layers of different types of concrete, were studied: NC in combination with FCC and FRFCC, with different doses of fibers. The interface, with and without chemical bond treatment, and the effect of fibers across the bond section surfaces, were also studied. Experimental characterization of used materials was also conducted.

From the results presented and the analysis developed, the following conclusions can be drawn:

- Hybrid beams reduce self-weight by about 13% against NC control beam.
- NC top layer in combination with FCC reduces the deformation of the structural element, against the one made completely with FCC. Which is an important issue on FCC and other LWC structural elements.
- Chemical treatment of the interface gets levels of rigidness for the hybrid beamshigher than those of NC.
- Bond strength development was satisfactory, even for the untreated cases. However, without treatment, interface failure at beams produces random behavior, against a totally linear one, in treated interfaces.
- The addition of fibers improves response to shear stress. It can be seen on hybridbeams and also in that made entirely of FCC.
- Fiber reinforcement shows to improve the rigidity of the beams entirely made of FCC. And in the case of hybrid, they highly reduce shear cracks amount and size.

No stability problems were observed in the studied specimens. No problems either at the casting procedure, although filling in 2 layers can take more time and effort, compared with elements made of single type concrete, especially for setting the chemical bond at the interface. Despite that, all the procedures are possible to be done on a building site. Some other variables could be studied in the future, such as long-term tests, and chemical resistance to aggressive environments, load-unload cycles, among others, for increasing the scope of this investigation.

Acknowledgements "Premoldeados Salamanca" enterprise, "Ferrocement" enterprise, and GEMA Investigation Group, from the Concepción del Uruguay Regional Faculty, National Technological University, Argentina.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

References

1. Retamal FA, Rougier VC (2022) apr). Mechanical behaviour, properties and characteristics of foamed cellular concrete: a review. Advan Mater Res 1170:61–85. https://doi.org/10.4028/p-ds0fcq

2. Narayanan N, Ramamurthy K (2000) Structure and properties of aerated concrete: a review. Cement Concr Compos 22(5):321–329. https://doi.org/10.1016/s0958-9465(00)00016-0
3. Retamal FA., and Rougier VC. (2021). Experimental study and development of an analytical model of stress-strain curve for foamed cellular concrete in uniaxial compression. 26º Argentine Conference on Structural Engineering, 1–15. ((In Spanish))
4. Jones M, McCarthy A (2005) Preliminary views on the potential of foamed concrete as a structural material. Mag Concr Res 57(1):21–31. https://doi.org/10.1680/macr.2005.57.1.21
5. Hoff GC (1972) Porosity-strength considerations for cellular concrete. Cement Concrete Res 2(1):91–100. https://doi.org/10.1016/0008-8846(72)90026-9
6. Nambiar EK, Ramamurthy K (2008) Models for strength prediction of foam concrete. Mater Struct 41(2):247–254. https://doi.org/10.1617/s11527-007-9234-0
7. Retamal FA, and Rougier VC (2021). Calibration of a strength prediction model for foamed cellular concrete. 19th LACCEI International Multi-Conference for Engineering, Education, and Technology: “Prospective and trends in technology and skills for sustainable social development” ”Leveraging emerging technologies to construct the future”, Buenos Aires -Argentina, 21–23:1–7. https://doi.org/10.18687/laccei2021.1.1.58
8. Dawood ET, Hamad AJ (2015) Toughness behaviour of high-performance lightweight foamed concrete reinforced with hybrid fibres. Struct Concr 16(4):496–507
9. Lee YL, Lim JH, Lim SK, Tan CS (2018) Flexural behaviour of reinforced lightweight foamed mortar beams and slabs. KSCE J Civ Eng 22(8):2880–2889. https://doi.org/10.1007/s12205-017-1822-0
10. Nes LG, Øverli JA (2016) Structural behaviour of layered beams with fibre-reinforced lwac and normal density concrete. Mater Struct 49(1):689–703. https://doi.org/10.1617/s11527-015-0530-9
11. Holschemacher K, Iqbal S, Ali A, Bier TA (2017) Strengthening of rc beams using lightweight self-compacting cementitious composite. Procedia Eng 172:369–376. https://doi.org/10.1016/j.proeng.2017.02.042
12. Iqbal S, Ali A, Holschemacher K, Bier TA, Shah AA (2016) jun). Strengthening of rc beams using steel fiber reinforced high strength lightweight self-compacting concrete (shlscc) and their strength predictions. Mater Des 100:37–46. https://doi.org/10.1016/j.matdes.2016.03.015
13. Iskhakov I, Ribakov Y, Holschemacher K, Mueller T (2013) feb). High performance repairing of reinforced concrete structures. Mater Des 44:216–222. https://doi.org/10.1016/j.matdes.2012.07.041
14. Iskhakov I, Ribakov Y, Holschemacher K, Kaeseberg S (2021) Experimental investigation of prestressed two layer reinforced concrete beams. Struct Concr 22(1):238–249
15. Iskhakov I, Ribakov Y (2007) A design method for two-layer beams consisting of normal and fibered high strength concrete. Mater Des 28(5):1672–1677. https://doi.org/10.1016/j.matdes.2006.03.017
16. De Sutter S, Verbruggen S, Tysmans T (2016) Shear behaviour of hybrid composite-concrete beams: experimental failure and strain analysis. Compos Struct 152:607–616. https://doi.org/10.1016/j.compstruct.2016.05.075
17. De Sutter S, Verbruggen S, Tysmans T (2016) Shear capacity of hybrid composite-concrete beams: a theoretical approach. Compos Struct 152:592–599. https://doi.org/10.1016/j.compstruct.2016.05.074
18. Aggelis D, Blom J, De Sutter S, Verbruggen S, Strantza M, Tysmans T, Nguyen P (2016). Fracture monitoring by acoustic emission: recent applications of parameter-based characterization. 9th international conference on fracture mechanics of concrete and concrete structures. 1021012/fc9.237
19. Karthik M, Maruthachalam D (2015) Experimental study on shear behaviour of hybrid fibre reinforced concrete beams. KSCE J Civ Eng 19(1):259–264
20. Usman F, and Hussin NM (2015). Flexural behaviour of hybrid concrete beam. The 3rd national graduate conference, university tenaga national, putrajaya campus (pp. 8–9).
21. ASTM (2016) C188–16. Stand Test Method Den Hydra Cement. https://doi.org/10.1520/C0188-17
22. ASTM (2012) C128: Standard test method for density, relative density (specific gravity), and absorption of fine aggregate. ASTM Int West Conshohocken. https://doi.org/10.1520/C0128-15
23. ASTM (2016) C127: Test method for relative density (specific gravity) and absorption of coarse aggregate. Annual Book of ASTM Stand ASTM Philadelphia PA. https://doi.org/10.1520/C0127-15
24. ASTM (2020). C143: Standard test method for slump of hydraulic-cement concrete., https://doi.org/10.1520/C0143 C0143M-20
25. ASTM (2021) C1611: Standard test method for slump flow of self-consolidating concrete. Stand Test Method Slump Flow Self-Consolid Concrete. https://doi.org/10.1520/C1611
26. ASTM (2021) C39: Standard test method for compressive strength of cylindrical concrete specimens. Annual Book of ASTM Standards, ASTM, Philadelphia, PA. https://doi.org/10.1520/C0039 C0039M-21
27. Momayez A, Ramezanianpour A, Rajaie H, Ehsani M (2004) Bi-surface shear test for evaluating bond between existing and new concrete. Materials Journal 101(2):99–106
28. Madhavi TC, Raju LS, Mathur D (2014) Polypropylene fiber reinforced concrete-a review. Int J Emerg Technol Adv Eng 4(4):114–118
29. Jhatial AA, Goh WI, Mohamad N, Hong LW, Lakhiar MT, Samad AAA, Abdullah R (2018) The mechanical properties of foamed concrete with polypropylene fibres. Int J Eng Tech 7(37):411–413
30. A.C.I., C. (2014). 523.3r-14: Guide for cellular concretes above 50 lb/ft^3 (800 kg/m^3). *American Concrete Institute*, 1–21.
31. Afifuddin M, Churrany M et al (2017) Shear behavior of fiber foam reinforced concrete beams. Procedia engineering 171:994–1001. https://doi.org/10.1016/j.proeng.2017.01.423
32. De Sutter S, Verbruggen S, De Munck M, Tysmans T (2016) Analytical modelling of the bending behaviour of hybrid composite-concrete beams Methodology and experimental validation. Appl Mathemat Model 40(23–24):10650–10666
33. De Sutter S, Verbruggen S, Tysmans T (2016) oct). Structural behaviour of hybrid composite-concrete floors: experimental validation and analytical simulation. Constr Build Mater 125:790–799. https://doi.org/10.1016/j.conbuildmat.2016.08.109
34. Hardjasaputra H, Ng G, Urgessa G, Lesmana G, Sidharta S (2017). Performance of lightweight natural-fiber reinforced concrete. J.-W. Park, H.A. Lie, H. Hardjasaputra, and P. Thayaalan (Eds.), Matec web of conferences . EDP Sciences. https://doi.org/10.1051/matecconf/201713801009
35. Holschemacher K, Iskhakov I, Ribakov Y, Mueller T (2012) Laboratory tests of two-layer beams consisting of normal and fibered high strength concrete ductility and technological aspects. Mech Adv Mater Struct 19(7):513–522. https://doi.org/10.1080/15376494.2011.556840
36. Iskhakov I, Ribakov Y, Holschemacher K (2017) Experimental investigation of continuous two-layer reinforced concrete beams. Struct Concr 18(1):205–215. https://doi.org/10.1002/suco.201600027
37. Ramamurthy K, Nambiar EK, Ranjani GIS (2009) A classification of studies on properties of foam concrete. Cement Concr Compos 31(6):388–396. https://doi.org/10.1016/j.cemconcomp.2009.04.006
38. Retamal FA, Rougier VC, Escalante MR (2020). Study of the mechanical behavior of simple cellular concrete and cellular

concrete reinforced with fibers in hybrid reinforced concrete beams. 15° International Congress of Pathology and Recovery of Structures (Complete articles): Materials, historical heritage, management and standardization, Catholic University of Salta Editions, 66–78. ((In Spanish))
39. Tam C, Lim T, Sri Ravindrarajah R, Lee S (1987) Relationship between strength and volumetric composition of moist-cured cellular concrete. Mag Concr Res 39(138):12–18. https://doi.org/10.1680/macr.1987.39.139.115
40. Vandewalle L, Nemegeer D, Balazs L, Di Prisco M (2002). Rilem tc 162-tdf: Test and design methods for steel fibre reinforced concrete: bending test.