Cement & Concrete Composites 26 (2004) 645–656

Cement & Concrete Composites

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Behavior in compression of lightweight fiber reinforced concrete confined with transverse steel reinforcement

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Received 21 March 2002; accepted 4 March 2003

Abstract

The compressive behavior of lightweight fiber reinforced concrete confined with transverse reinforcement consisting of steel stirrups or spirals was analyzed. Pumice stone and expanded clay aggregates were utilized to decrease the weight of the composite; hooked steel fibers were also added. The investigation was carried out by testing cylindrical and prismatic specimens of different sizes in compression using an open-loop displacement control machine, recording the full load–deformation curves. The influence of the dimensions and shape on the bearing capacity and on the ductility of the specimens confined with transverse steel reinforcements was analyzed. The results show the possibility of obtaining high confinement level through the coupled effect of fibers and steel transverse reinforcement.

Keywords: Lightweight concrete; Pumice stone; Expanded clay; Steel fibers; Steel transverse reinforcement; Compression tests; Stress–strain curves; Shape effects

1. Introduction

Lightweight concrete, besides being utilized for its non-structural properties has also been employed to make structural elements, in particular in the field of precast concrete structures. Maintaining an adequate strength level, lightweight concrete permits a reduction in the horizontal inertia actions on structures in seismic regions, exerts a favorable effect on the reduction of the dimensions of the foundations of buildings supported by soil having low bearing capacity, and facilitates the transport of precast concrete elements.

The physical and mechanical properties of lightweight concrete greatly depend on the aggregates utilized and in particular on their density. In general, greater aggregate density improves the strength of the material, though there is an increase in self-weight. In any case, the most evident restriction to the structural use of this material is the brittleness by which it is affected. This disadvantage can be overcome by increasing the ordinary confinement transverse steel reinforcement with respect to that required in normal weight concrete [1–5] having same maximum strength, or by adding reinforcing fibers to the concrete matrix, as shown in several recent studies [6–8].

Several theoretical and experimental investigations have pointed out the influence of the type and arrangement of the confining reinforcement, depending on the shape of the transverse cross-section, on the strength and the ductility of the normal weight concrete elements under compressive loads.

If lightweight concrete is used similar effects are expected [9–14] but larger amounts of transverse reinforcing steel are required due to the brittle nature of the composite [1,15]; the placing of such transverse steel entails much effort and cost.

To simplify the fabrication process in critical regions, the use of fiber reinforced concrete (FRC) is desirable to ensure ductile behavior. However, for the rational design of concrete structures the complete stress–strain curves should be determined for all the constituent materials, including FRC in combination with conventional reinforcement.

This experimental study, based on compressive tests, emphasizes the favorable effect of fibers in lightweight concrete with pumice stone or expanded clay aggregates.

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doi:10.1016/S0958-9465(03)00047-7

Nomenclature

A_s	transverse cross area of spiral or stirrup
b	dimension of transverse cross-section of prismatic specimen
b^*	side length of prismatic specimen
d	diameter of steel spiral between bar centers
d^*	diameter of cylindrical specimen
f'_c	compressive strength of concrete at 28 days
f'_{cc}	compressive strength of confined concrete at 28 days
f_l	confinement pressure
f_y	yielding strength of steel spiral or stirrup
L_f	length of fiber
s	spiral or stirrup spacing
V_f	volume fraction of fibers
ρ_s	ratio of volume of transverse confining steel to volume of confined concrete core
ϕ	diameter of fiber

The results described below confirm that the presence of hooked steel fibers influences the response in compression, especially in the post-peak behavior; moreover, if fibers are utilized coupled with conventional steel reinforcement, strength and ductility improve significantly.

2. Parameters affecting experimental compressive response

The main parameters affecting the compressive behavior of concrete during the tests are [16]: the frictional restraint between the loading platens and the specimen; the allowable rotations of the loading platens before and during the test; the gauge length of the control LVDT (conventional displacement controlled test); the stiffness of the testing machine; the type of feed-back signal; the loading rate; the shape and the size of the test specimen; the concrete composition. The standard tests generally involve the loading of the specimen between rigid steel loading platens, but it would be preferable to reduce to a minimum the friction between the loading platens and the specimen. When steel platens are used, as is prescribed in most test methods, triaxially confined zones develop in the parts of the specimens in contact with the loading platens. This leads to a higher measured strength at low height to diameter ratios of the cylindrical specimens, because the triaxially restrained zones include most of the specimen. When lubricated loading platens (teflon and grease) are used, this increase in strength does not occur [16].

The loading platens should be fixed against rotation once a significant load is applied to the specimen. However, before this stage, some rotation of the upper platen is required, as the specimen ends are rarely parallel. Often, capping of the specimen ends is used to ensure plane and parallel ends.

Axial deformations are generally recorded using LVDTs. The gauge length of the control LVDTs in a conventional displacement controlled test is chosen to be equal to the specimen length (i.e. from platen to platen), but it would be more appropriate to choose a gauge length reduced with respect to the entire length of the specimens to avoid extraneous effects, due to the boundary conditions of the tests, affecting the results.

Regarding the testing procedure, a more accurate control would be a closed-loop, servo-controlled loading system. In this case, the axial deformation can be used as a feed-back signal [16], but it may not always be appropriate for controlling the test in the post-peak branch if snap-back occurs or if the post-peak curve is very steep. In these cases, some investigators [17,18] have proposed lateral deformation instead of axial deformation as the feed-back signal. Unfortunately, a closed-loop servo-controlled loading system is not always available, and very often open-loop testing machines, with displacement control, are used to test concrete in compression. Depending on the rate of displacement chosen for the test, the stiffness of the testing machine, the size of the concrete member and the strength of the material, it is possible to perform a stable test, but if snap-back occurs erroneous results are obtained.

3. Experimental program

3.1. Material properties

Two different mixes were used to investigate the influence of different types of aggregate on the behavior of lightweight FRC. Hooked steel fibers were utilized at different percentages both in the presence and in the absence of traditional steel reinforcements. Fibers having length $L_f = 30$ mm, and diameter $\phi = 0.5$ mm (with aspect ratio $L_f/\phi = 60$) were randomly distributed in the fresh concrete mixture. The volume percentages of fibers were 0.5%, 1% and 2% by volume of concrete, corresponding to fiber amounts of 40, 80 and 160 kg/m^3, respectively. The minimum nominal tensile strength of the fibers was equal to 1115 N/mm^2. The mix designs of lightweight plain concretes already utilized in a previous investigation [14] are given in Table 1, where L_p denotes

Table 1
Mix proportions for concrete (kg/m^3)

Component	L_p	L_c	N_r
Cement (Ptl 425)	350	350	300
Water	135	135	180
Pumice aggregate size from 3 to 7 mm	320	/	/
Pumice aggregate size from 7 to 10 mm	170	/	/
Expanded clay aggregate size from 3 to 7 mm	/	320	/
Expanded clay aggregate size from 7 to 17 mm	/	170	/
Coarse aggregate (⩽10 mm)	/	/	1050
Natural sand	782	782	850

a lightweight concrete matrix with pumice stone coarse aggregate, L_c a lightweight concrete matrix with expanded clay coarse aggregate, and N_r a normal weight concrete matrix, the latter being manufactured with conventional aggregates about the same size as lightweight aggregates, in order to make the different performances comparable. Pumice stone aggregate with a size from 3 to 7 mm (mean size) and from 7 to 10 mm (great size) was used. The fine portion (<3 mm) of the pumice stone was removed and substituted by medium sand in order to improve the mechanical properties of the concrete. The expanded clay aggregates, almost round but irregular in shape with a maximum diameter of 17 mm, had an apparent weight density of 650 kg/m^3. Medium size aggregate with diameter from 3 to 7 mm and large size aggregate with diameter from 7 to 17 mm were used. In the mixture with expanded clay the share of fine material was also removed. Before mixing lightweight aggregates were placed in a tank full of water for half an hour. All matrices were prepared using type 425 Portland cement produced in Italy and having similar characteristics to ASTM type I cement. The mix design for normal weight concrete (particularly the water/cement ratio) was chosen to give comparable strength with respect to lightweight concrete. The weight density of hardened concrete without reinforcing fibers proved to be 1800, 1640 and 2420 kg/m^3 for lightweight concrete with pumice stone, lightweight concrete with expanded clay and normal weight concrete, respectively.

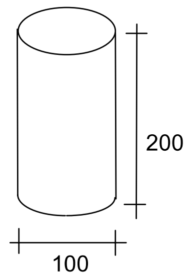
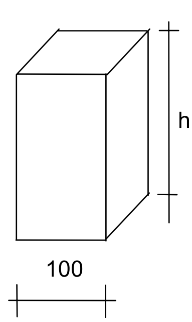
3.2. Specimens

To study the behavior in compression of the lightweight concrete, specimens having different shapes (cylindrical and prismatic), and different dimensions were prepared. Cylindrical specimens 100×200 mm were cast using either lightweight concrete with pumice stone or expanded clay. Prismatic specimens with transverse cross-section 100×100 mm and different height, 100, 200 or 340 mm, were cast using lightweight concrete with expanded clay aggregates. Additionally, in order to make a comparison in the performance, cylindrical specimens of 100×200 mm and prismatic specimens with height 200 mm were cast using normal weight concrete. For each series, obtained by varying the amount of fibers or transverse confining steel reinforcement, three specimens were prepared. Geometrical details of specimens are given in Table 2. The confining reinforcement with rebars of diameter 4 mm and area given as A_s, consisted of circular spirals for cylindrical specimens and of square stirrups for prismatic specimens; they were constructed with steel wires having a yielding stress value $f_y = 520$ MPa. The circular spirals, at pitches of $s = 25$ or 50 mm, were placed in cardboard cylinder molds with internal diameter 100 mm and length 200 mm. An effective external diameter of 85 mm was provided for the spirals. The percentages of the steel spirals were $\rho_s = 4A_s/(d \times s) = 2.48\%$ and 1.24% respectively, d being the diameter of the spiral between bar centers; the corresponding values of maximum confinement pressure were $f_l = 2f_yA_s/(d \times s) = 6.45$ and 3.22 MPa, respectively. The square stirrups, at pitches of $s = 20$ or 40 mm, were placed in cardboard molds with internal dimension 100 mm and length 100, 200, and 340 mm, depending on the sizes of the specimens tested. An effective external side of 85 mm was provided for the stirrups and longitudinal bars of the same diameter were used to maintain the distance between the stirrups unchanged. The percentages of the steel stirrups were $\rho_s = (4 \times A_s)/(b \times s) = 3.10\%$ and 1.55% respectively, b being the side of the stirrups between bar centers; the corresponding values of maximum confinement pressure were $f_l = 2f_yA_s/(b \times s) = 8.06$ and 4.03 MPa.

3.3. Test set-up

The concrete specimens were subjected to uniaxial monotonic compression in order to obtain the stress–strain curves. All the tests were carried out in the presence of friction at the ends of the specimens, due to the presence of end steel plates and because no special devices (teflon, grease, brushes) were utilized. The specimens were tested using an open-loop machine having a spherical joint at the top and a maximum load capacity of 600 kN. To obtain the complete curve in compression a slow rate of displacement, 0.2 mm/min, was employed.

Table 2
Geometrical characteristics of specimens

Aggregate type	Shape and dimensions (mm)	V_f (%)	ρ_s (%)
Pumice stone or expanded clay		0	/
		0.5	/
		1.0	/
		2.0	/
		0	1.24
		0	2.48
		1	1.24
		2	1.24
Expanded clay $h = 100$, 200, 340 mm		0	/
		0.5	/
		1.0	/
		2.0	/
		0	1.55
		0	3.10
		1	1.55
		2	1.55

For normal weight plain concrete only 100×200 mm cylindrical and $100 \times 100 \times 200$ mm prismatic specimens were prepared.

Though, as stressed in the previous section, in order to record the post-peak behavior of plain concrete (especially if high strength matrices are utilised) in a stable manner a displacement control with a closed-loop testing machine is required, in the case of low strength concrete confined by fibers or transverse steel, it is possible to record the softening branch of the response in a stable manner utilising a very stiff testing machine operating in a displacement control mode and in open loop mode, as also shown in [1]. This approach is also in agreement with the experimental procedure proposed by Japanese recommendation [19] regarding the evaluation of compressive toughness of FRC.

The axial deformations were measured using three digital transducers placed in two metal rings on a gauge length of 140 mm and they were located in plan in such a way as to form an angle of 120° with one another. In the case of cubical specimens with 100 mm sides the entire length of the specimen was adopted as the gauge length. An electronic data acquisition system was used to record deformations and corresponding loads.

3.4. Investigation criteria

The results obtained in the compressive tests are presented below in the form of σ–ε curves, in which the stress value σ is assumed to be the ratio between the load value provided by the load cell and the nominal value of the cross-section of the specimen; the strain value ε is obtained as the mean value of the measured deformation referred to the gauge length.

All the stress–strain curves illustrated in the following sections are obtained as the mean curves of the curves referring to the three different specimens for each series investigated.

The experimental results stress the influence of the following parameters on the behavior in compression:

- volume percentage of fibers;
- type and volumetric ratio of transverse steel reinforcements;
- shape of specimens (prism, cube, cylinder);
- length of prismatic specimens.

In the following sections, results relative to cylindrical 100×200 mm specimens showing the influence of aggregate types, volume percentage of fibers and/or steel spirals are discussed; then the shape effect is investigated by comparing the influence of different volume percentages of fibers and/or of transverse steel reinforcements on the behavior of prismatic and cylindrical specimens of lightweight concrete with expanded clay having dimensions 100×200 mm; finally, the effects of the length of the prismatic specimens reinforced with different volume percentages of fibers and/or transverse steel reinforcements were evaluated by testing in compression specimens of lightweight concrete with expanded clay aggregates with three different lengths.

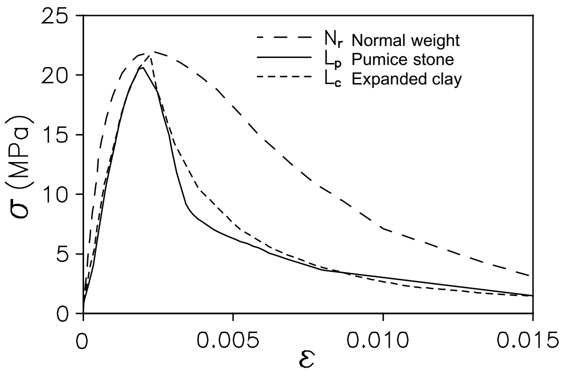


Fig. 1. Stress–strain curves for plain concrete cylinders.

4. Response in compression

4.1. Lightweight concrete cylinders

Fig. 1 shows the average monotonic response of the 100×200 mm cylindrical specimens in compression, for the three types of concrete matrix considered (with pumice stone, with expanded clay, with normal-weight coarse aggregate). The shapes of the curves show that lightweight and normal weight concrete exhibit about the same strength, but lightweight concrete is affected by brittle behavior with both pumice stone aggregates and expanded clay aggregates. The different behavior can be explained by considering that in lightweight concrete matrices failure mainly involves the aggregates rather than the cementitious matrix, whereas the latter is more subject to failure in normal weight concrete. It should also be observed that stress–strain curves referring to lightweight concrete with pumice stone or expanded clay cannot easily be compared because of their different shapes and the maximum size of the aggregates chosen.

4.2. Lightweight fiber reinforced concrete cylinders

Fig. 2 shows the favorable effect of fibers on the monotonic response in compression of lightweight concrete matrices, in particular in the softening branch. The addition of fibers in lightweight concrete cylinders with pumice stone does not determine increases in maximum strength, as instead occurs in the case of lightweight concrete with expanded clay, for which an increments of about 30% in maximum strength was observed. This is probably due to the unfavourable fiber length/maximum aggregate size ratio chosen in lightweight concrete with pumice stone.

However, in both cases the presence of fibers increases the residual strength and the energy absorbed up to failure. In the case of normal weight FRC, similar results are obtained in the literature [6], in a slight increase up to 15% in maximum strength being observed when 3% by volume of fibers is utilized.

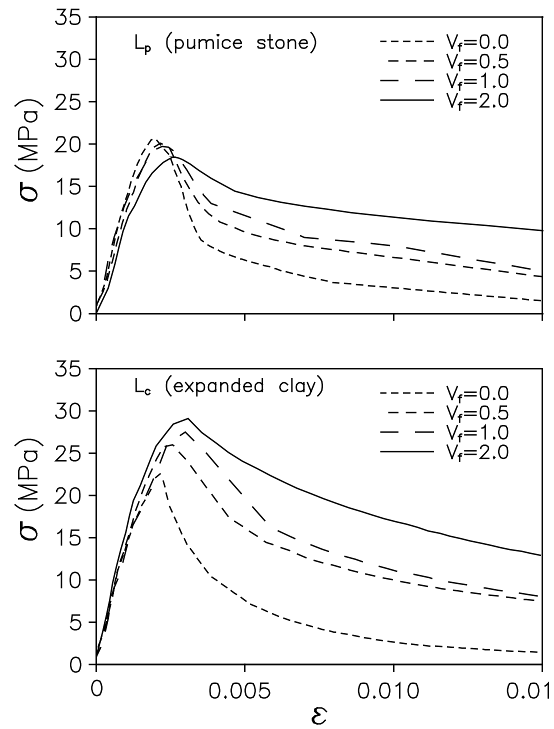


Fig. 2. Stress–strain curves for FRC cylinders.

Although the number of specimens (three for each series) is too low to give statistical values, scatters of maximum strength values were (in terms of scatter square root of maximum strength) $R^2 = 0.94$ for lightweight plain concrete and $R^2 = 0.88$ for lightweight fiber reinforced concrete.

4.3. FRC lightweight cylinders with steel spirals

Compressive tests on cylindrical specimens confined with steel spirals were carried out to evaluate the confinement effect on lightweight fiber reinforced concrete in the presence of traditional transverse reinforcement.

In Figs. 3 and 4 the stress–strain curves are shown for the cases of pumice stone and expanded clay aggregate respectively. Each diagram contains results derived considering the two different percentages of steel spirals defined above and the volume percentages of fibers $V_f = 1$ and 2%. The cases of $\rho_s = 0\%$ and $V_f = 0\%$ are also considered. The curves show that adding both fibers and steel spirals produces an increase in the bearing capacity and in the residual strength with respect to the case of steel spirals or fibers only.

The comparison between the curves obtained in the absence of fibers ($V_f = 0\%$), for both pumice stone and expanded clay, shows increases in the bearing capacity of lightweight concrete due to steel spirals. However, this effect is less marked than that obtained in normal weight concrete when the same percentage of steel spirals is adopted. This circumstance is due to the lower

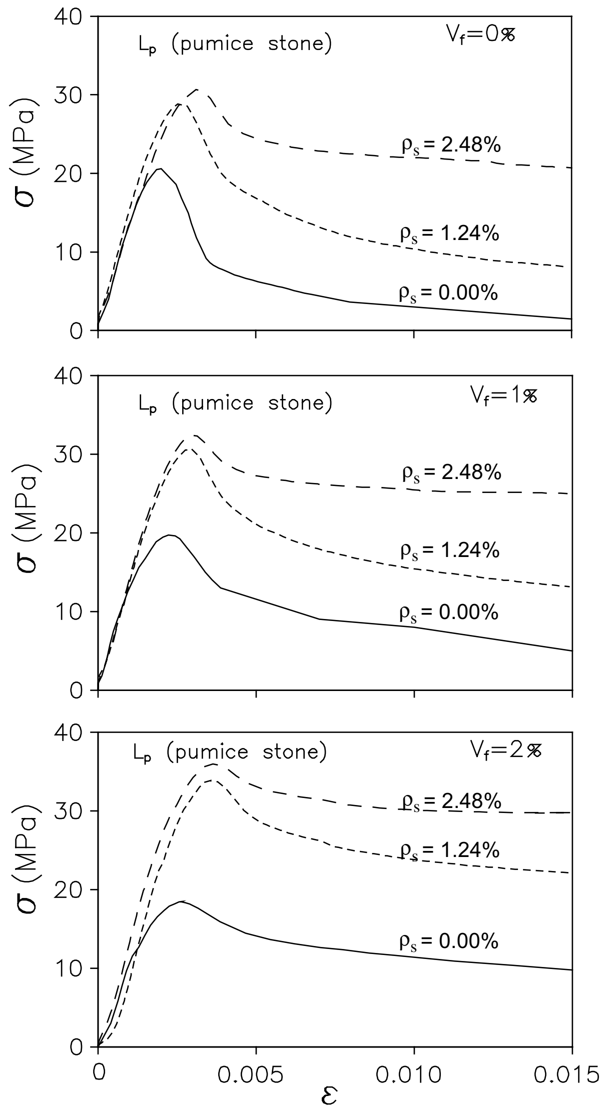


Fig. 3. Stress–strain curves for confined FRC concrete cylinders with pumice stone.

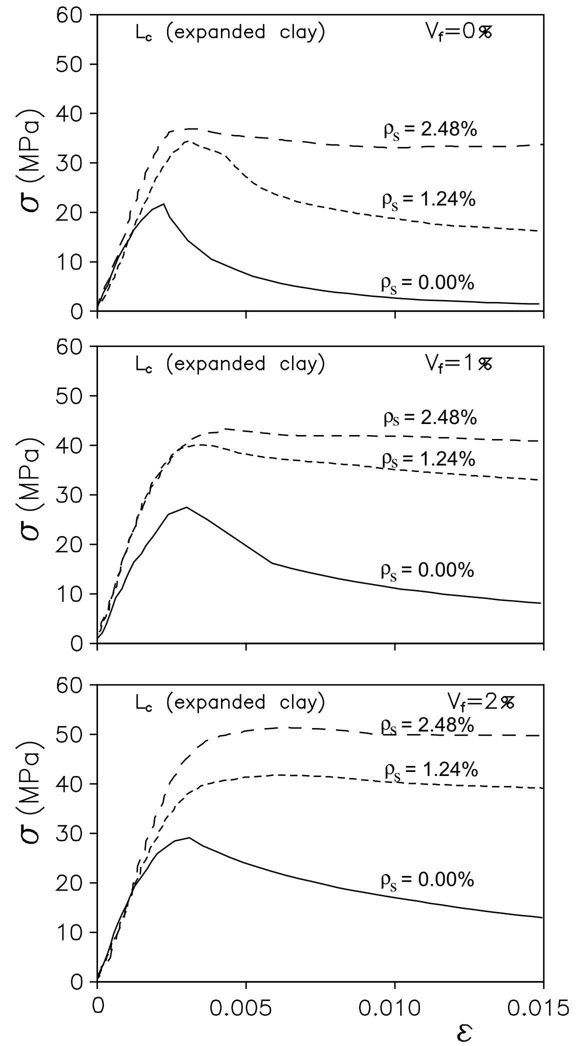


Fig. 4. Stress–strain curves for confined FRC concrete cylinders with expanded clay.

lateral expansion of lightweight concrete with respect to normal weight concrete, which produces a consequent lower lateral confining pressure, as also observed in the literature [1,9]; moreover, it is due to the brittle nature of lightweight aggregate, leading to premature failure of the specimen before the yield stress in the steel spirals is reached.

Figs. 5 and 6 show the failure mode of cylindrical specimens in lightweight concrete with expanded clay, with and without fibers (Fig. 5) and in the presence of steel spirals, with and without fibers (Fig. 6). The failure of the specimens in the absence of fibers is a mixed mode of split and twin cone failure, which becomes a mode of failure characterized by inclined finer widespread cracks in the case of a higher percentage of fibers.

In the case of steel spirals the failure mode in the specimens involves an inclined plane in concrete across a

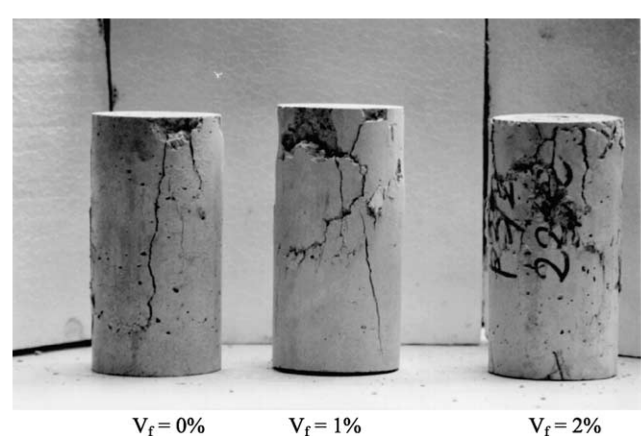


Fig. 5. Failure modes of lightweight expanded clay concrete cylinders.

pitch of steel spiral. From observations of the failure mode, the following considerations emerge: (1) due to the poor strength capacity of the lightweight aggregate,

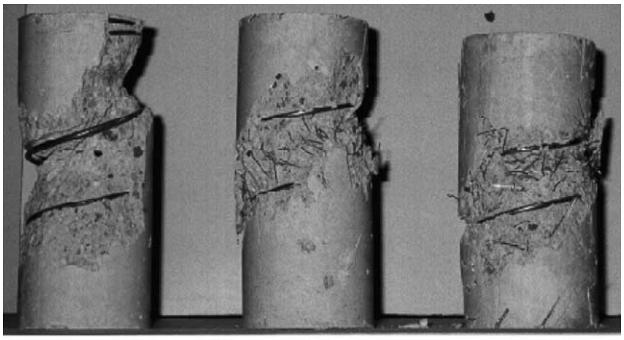


Fig. 6. Failure modes of lightweight expanded clay FRC cylinders with steel spirals at pitch $s = 50$ mm ($\rho_s = 1.24\%$).

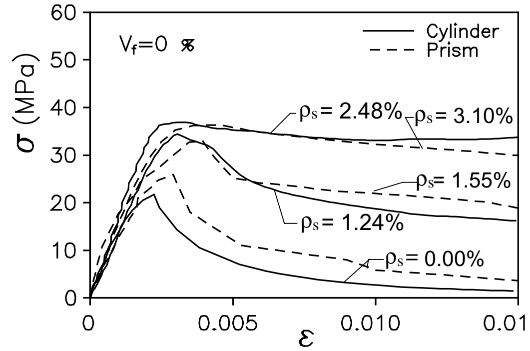


Fig. 8. Comparison between σ–ε curves of cylindrical and prismatic confined 100×200 mm concrete specimens with expanded clay aggregates.

failure does not occur in steel spirals; (2) the brittle nature of lightweight aggregate makes it impossible to mobilize high values of interlock forces implying significant residual strength. The addition of fibers modifies the failure mode: it becomes more dissipative due to the pull-out forces in the fibers, and it involves a reduced region of cover expulsion.

Fig. 7 shows the possibility of obtaining the same performance in terms of strength and energy absorption capacity using fibers and steel spirals in a lower percentage or using only a higher percentage of spirals. In particular, the curves refer to the following values: $\rho_s = 2.48\%$ and $V_f = 0\%$ or $\rho_s = 1.24\%$ and $V_f = 2\%$ for the case of pumice stone; $\rho_s = 2.48\%$ and $V_f = 0\%$ or $\rho_s = 1.24\%$ and $V_f = 1\%$ for expanded clay. These results also confirm that the confining effect due to the fibers is more evident for concrete with expanded clay. The results in Fig. 7 are very meaningful for practical applications, because the coupled use of steel spirals in a lower percentage and fibers makes the fabrication of structural elements easier than in the case of higher percentages of steel transverse reinforcements. It is to be noted that the results obtained are essentially of a qualitative nature, because the specimen height and size chosen are small with respect to the tie spacing. For this

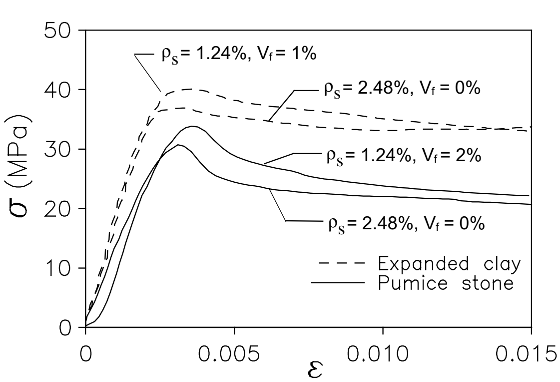


Fig. 7. Comparison between stress–strain curves for FRC cylinders with steel spirals.

reason, benefit effects in terms of strength and strain capacity increases deduced on small size specimens reinforced with fibers and/or with reinforcing transverse steel have to be considered reduced in real structures. Nevertheless, the results obtained are in agreement with those shown in the literature regarding specimens with similar size, type and arrangement of transverse steel [20,21].

4.4. Shape effects

Fig. 8 gives the stress–strain curves for cylindrical and prismatic unconfined and confined concrete specimens with expanded clay having the same length (200 mm). The transverse reinforcement was constituted, as already mentioned, by steel spirals for cylindrical specimens and by steel stirrups for prismatic specimens.

Experimental results have shown that the presence of transverse reinforcement, as expected, produces a significant increase in the strength value and in the strain capacities. The graph shows also that the confinement effect both in terms of strength and strain capacities are quite the same for cylindrical specimens with steel spirals and for prismatic specimens confined with steel stirrups: the maximum lateral pressure chosen for prismatic specimens is higher than that in cylindrical specimens, because the effective confined square cross-section is reduced with respect to the circular cross-section.

In the presence of transverse steel reinforcement and fibers better performance was obtained for cylindrical specimens with respect to prismatic specimens, as shown by the curves in Fig. 9. From the results it emerges that the presence of fibers in addition to transverse steel reinforcements produces better performance for both prismatic and cylindrical specimens with respect to the case in which only transverse steel reinforcements are used, but the shape of the cross-section produces different effects because the effectively confined core is higher in cylindrical specimens with respect to that of

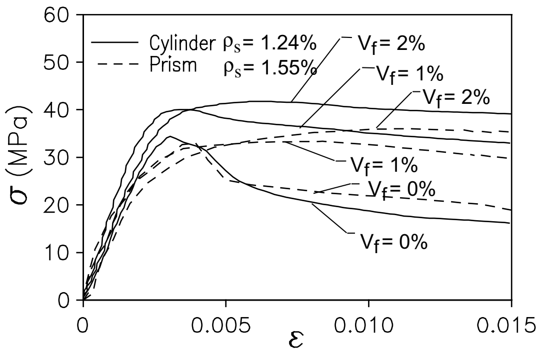


Fig. 9. Comparison between σ–ε curves of cylindrical and prismatic confined FRC 100×200 mm concrete specimens with expanded clay aggregates.

prismatic specimens with stirrups, the shape of the section playing an important role in the material properties.

5. Effect of specimen length

To study the effect of specimen length on the properties of lightweight FRC also having transverse steel reinforcements, prismatic specimens obtained with expanded clay, having different heights (100, 200, 340 mm), were tested in compression.

The choice of the dimensions is linked to the following considerations:

- prisms with 100 mm sides are commonly contemplated in testing codes;
- prisms with height 200 mm were chosen for comparison with cylinder of the same height;
- prisms with height 340 mm were chosen for estimate the influence of the slenderness of the specimens and to measure the deformations in a region not affected by boundary factors.

5.1. Effect of transverse steel reinforcement

The nominal stress–strain curves for the different size specimens of unconfined and confined concrete with steel stirrups are shown in Fig. 10.

With an increase in the slenderness of the specimens, lightweight concrete appears to exhibit a more brittle behavior, and the strength decreases slightly.

These results are consistent with those reported in a RILEM Round Robin test series [16], carried out on both prisms and cylinders of normal weight concrete, with friction between the specimen ends and the loading platens. These tests showed as well a slight reduction in apparent strength for rigid platens as the slenderness (height/diameter) increased. Similar results for specimens tested with reduced end friction were found by Jansen and Shah [17], and by Jansen et al. [18]. The

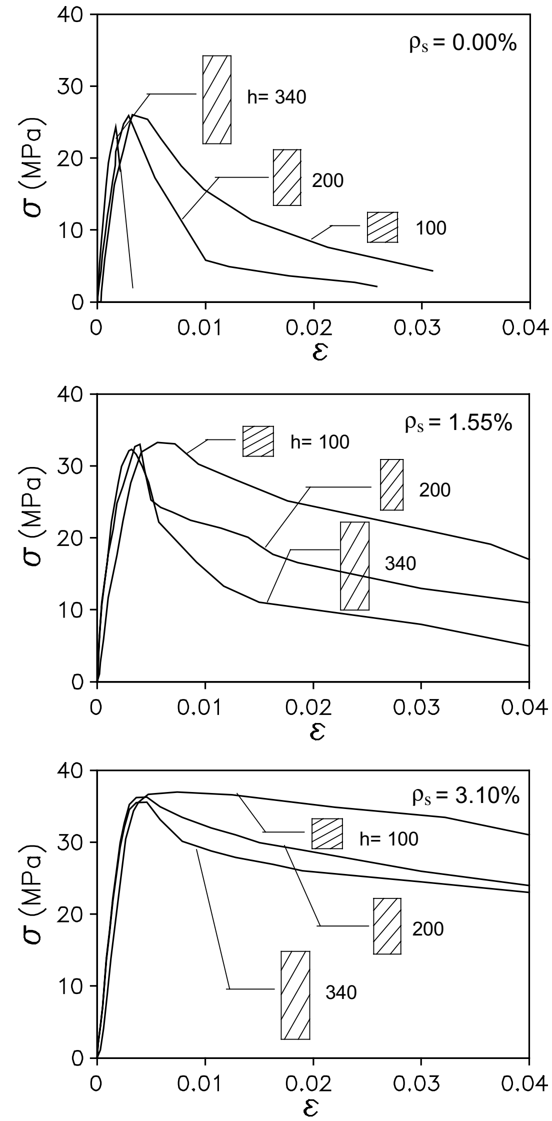


Fig. 10. Stress–strain curves for confined lightweight concrete prisms of different sizes with expanded clay aggregates.

apparent strength mentioned in the text is the ratio between the actual load and the area of the transverse cross-section. It is defined apparent because it is only a conventional parameter, being affected, especially in the post-peak range, by several factors, e.g. size of the specimens, type of tests, rate of loading, etc.

The presence of transverse steel reinforcement clearly provided more effective confinement, leading to both a higher apparent compressive strength, and a somewhat reduced size effect in terms of peak strength. Also, as already observed in the case of plain concrete, a more brittle failure (steeper slope in the descending branch of the σ–ε curves) was observed for the more slender specimens.

If a very high volume percentage of transverse steel reinforcement is utilized ($\rho_s = 3.10\%$) a reduced size effect, also in terms of maximum and residual strength, is observed; results are also in agreement with those observed in the literature [1] for cylindrical specimens.

5.2. *Effect of fibers or fibers and transverse steel reinforcement*

Typical results of tests on lightweight concrete prisms of different sizes and reinforced steel fibers with amounts of 0.5%, 1.0%, 2.0% by volume are shown in Fig. 11. For FRC too, a size effect was observed in terms of maximum strength. For FRC with a high volume fraction of fibers more residual strength (it is the apparent strength measured in the softening branch) was observed and the apparent strength measured in the softening branch appeared not to depend very much on the dimensions of the specimens. These phenomena can be explained by observing that in specimens reinforced with a high volume fraction of fibers the failure mode is more ductile, because it is related to the pull-out mechanism of the individual fibers.

Fig. 12 shows analogous results to Fig. 11, but referring to the case of coupled use of fibers and steel stirrups. In this case more effective confinement produced higher strength in smaller specimens and size effect was also observed in terms of residual strength but this effect was reduced with an increase in the volume percentages of fibers.

As already observed for cylindrical specimens, for prismatic specimens made of lightweight concrete with expanded clay aggregates, the addition of fibers also determines increases in maximum strength, which in the

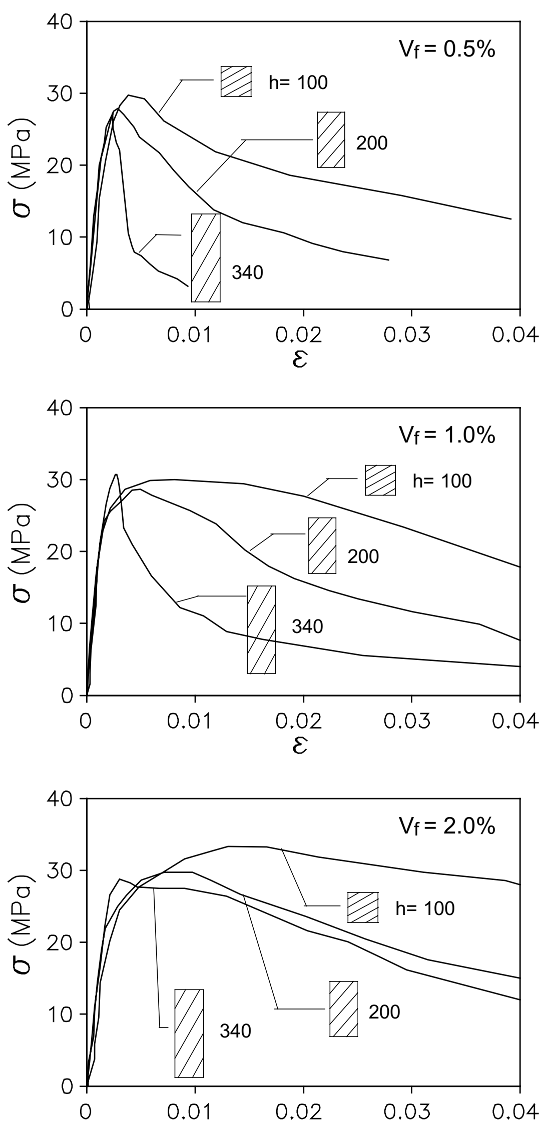


Fig. 11. Stress–strain curves for lightweight FRC prisms of different sizes with expanded clay aggregates.

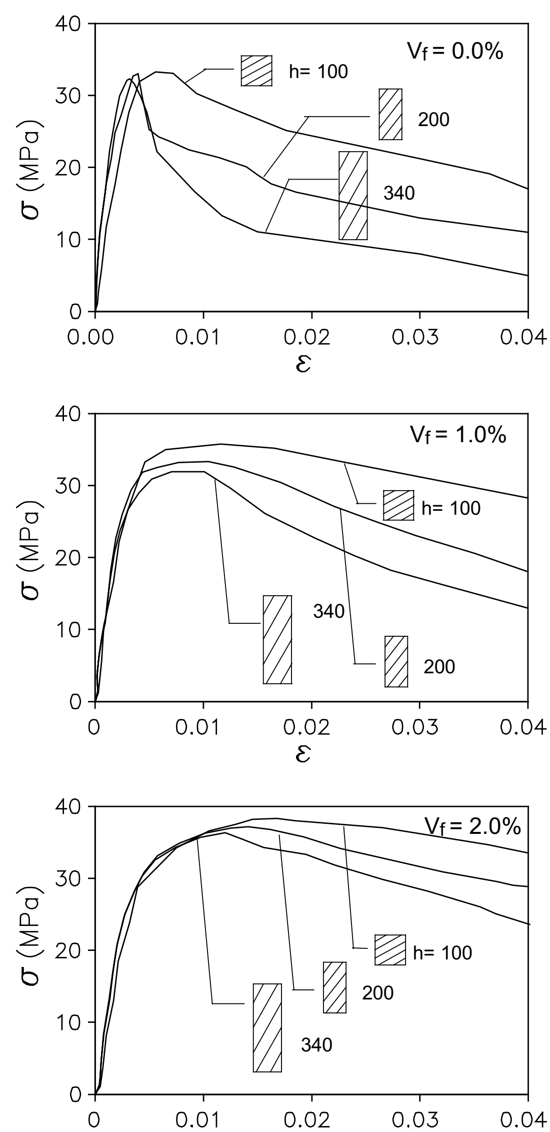


Fig. 12. Stress–strain curves for confined lightweight FRC prisms of different sizes with expanded clay aggregates and with $\rho_s = 1.55\%$.

case of 2% of fibers were 20% and 35% respectively for 100×100 and 100×340 mm prismatic specimens.

Figs. 13 and 14 show the failure mode and the confinement effect of transverse steel stirrups in lightweight expanded clay concrete prisms with variation in length.

It is interesting to observe that, the steel bars having a small area compared to the gross concrete area of transverse cross-section and reduced length with respect to the entire length of the specimen, only a small portion of the external axial load was supported by the longitudinal steel bars by adherence. Moreover, in the case of a small amount of transverse steel, when the ultimate load is reached expulsion of the concrete core occurs and a buckling effect in longitudinal bars arises, reducing the strength contribution due to yielding of longitudinal bars.

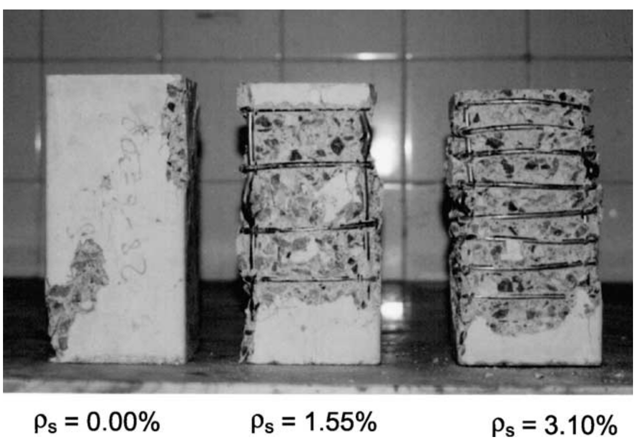


Fig. 13. Mode of failure of expanded clay lightweight 100×200 prisms confined with steel stirrups.

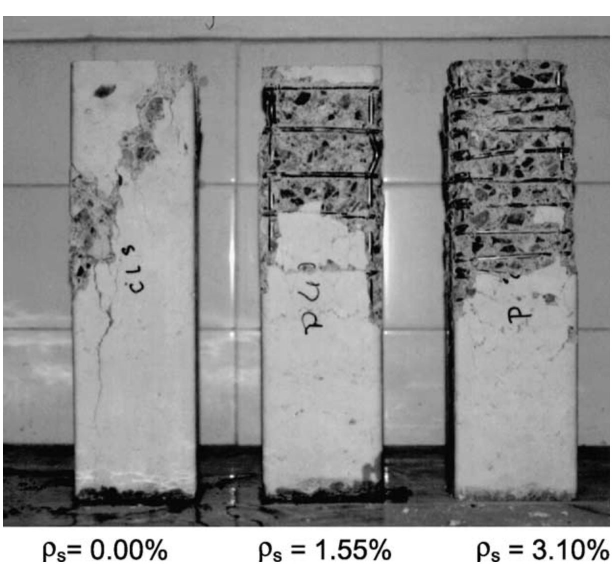


Fig. 14. Mode of failure of expanded clay lightweight 100×340 prisms confined with steel stirrups.

6. Comparison with experimental results available in the literature

In the present section some experimental results on the influence of transverse steel reinforcements on confinement effectiveness in lightweight concrete, presented in the literature [1,9,15] are given for comparison with the results of the present investigation. The results obtained in the experimental investigations mentioned refer to tests carried out on specimens having geometry and test set-up similar to those of the present investigation. For example, in [1] small cylindrical specimens (ranging from 102×203 to 102×407 mm) were tested in a stiff testing machine operating in displacement control mode with a low displacement rate. These specimens were reinforced with steel spirals constituted by steel wire ranging from 3 to 7 mm in diameter and having yielding stress up to 414 MPa and a geometrical percentage of transverse steel referred to the cross-section similar to that adopted in the present research.

In Fig. 15 the increase in maximum strength f'_{cc}/f'_c with the effective lateral pressure $f_l(1 - s/d)$ is given for both normal weight and lightweight concrete showing that the experimental results obtained are in agreement with those given in the literature, and also showing that the confinement due to the presence of steel spirals is more effective for normal weight concrete than for lightweight concrete. The term $1 - s/d$ reflects the observation that confinement is almost ineffective if the

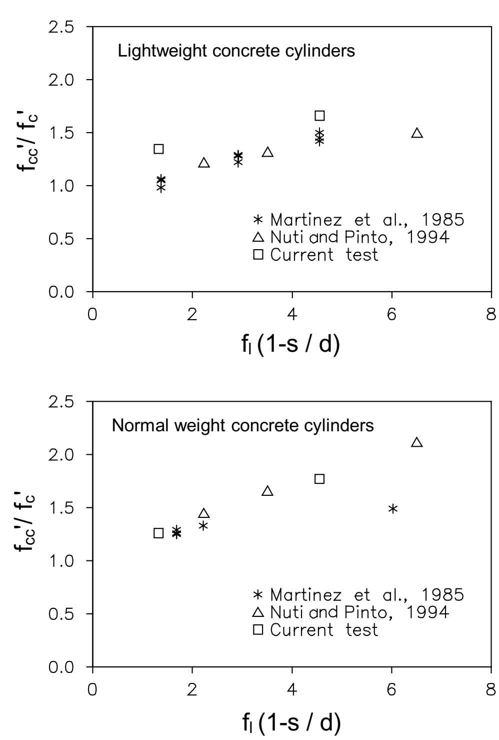


Fig. 15. Comparison with data available in the literature regarding confinement effects due to transverse steel reinforcements.

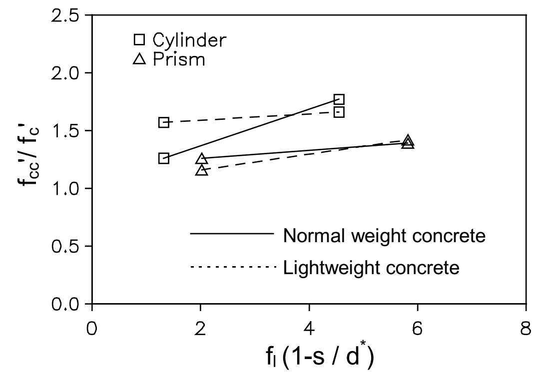


Fig. 16. Comparison between confinement effects due to transverse steel reinforcements on prismatic and cylindrical specimens (for prismatic specimens $d^* = b^*$).

pitch becomes equal to the spiral diameter [1]. Similar results present in the literature [15] have pointed out the influence of the shape of the cross-section; in particular for an elliptical cross-section of lightweight concrete columns confined by single hoops an increase of up to 1.29 of the compressive strength was observed with 1.73% of transverse steel reinforcements.

In order to point out that shape of the cross-section plays an important role in the confinement due to transverse steel (stirrups for prisms and steel spirals for cylinders) also in the case of lightweight concrete in Fig. 16 is given the increase in maximum strength f'_{cc}/f'_c with the effective lateral pressure $f_l(1 - s/d)$ for circular and prismatic specimens; less effective confinement is observed with respect to normal weight concrete.

7. Conclusions

Based on compressive tests on small size (100 × 200 mm) cylinders of lightweight FRC in the presence of steel spirals, the following conclusions can be drawn:

1. Very brittle behavior of lightweight concrete is observed in the case of both pumice stone and expanded clay under monotonic loads.
2. The addition of fibers increases the residual strength and the energy absorption capacity; moreover for expanded clay it produces a significant increase in the bearing capacity while for pumice stone no significant variation is observed.
3. In the presence of fibers, concrete reinforced with steel spirals shows an increase in the strength and corresponding strain and in the energy absorbed compared to plain concrete confined by steel spirals.
4. The reinforcing fibers can partially substitute the transverse reinforcement in an adequately balanced way, avoiding the difficulty connected to placing a large quantity of steel confining reinforcement often required by the seismic codes to ensure high performance in ductility terms in the dissipative regions.

It has been shown that for lightweight concrete, shape and dimension effects play a fundamental role in test results and in particular:

5. Due to the shape effects, confinement properties connected to the presence of transverse steel reinforcements observed in the case of lightweight prisms are reduced with respect to the case of cylinders. In the presence of fibers and/or transverse steel reinforcements very good and comparable performances are observed both for cylindrical and prismatic specimens and shape effect plays a marginal role.
6. With an increase in the length of the specimens considered, a slight reduction in maximum strength was observed for unconfined concrete, and in the presence of fibers and/or transverse steel reinforcements a very slight reduction in terms of both maximum and residual strength was observed.

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