13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2087

EXPERIMENTAL INVESTIGATION ON LOCAL BOND-SLIP BEHAVIOUR IN LIGHTWEIGHT FIBER REINFORCED CONCRETE UNDER CYCLIC ACTIONS

Giuseppe CAMPIONE[1], Calogero CUCCHIARA[2] Lidia LA MENDOLA[3] and Maurizio PAPIA [4]

SUMMARY

Experimental results of the local bond stress-slip relationship of reinforcing bars embedded in lightweight fiber reinforced concrete with expanded clay aggregates are presented. For fixed diameter of steel bars and confinement external transverse pressure value, the effect of different percentages of hooked steel fibers and different geometrical ratios of transverse reinforcement was investigated. Prismatic specimens with longitudinal steel bars embedded for a fixed length were tested under both monotonic and cyclic reversal imposed displacements at the tip of the bars, in controlled displacement tests. The influence of the above mentioned parameters was investigated, and the effects in terms of strength and ductility of the confinement due to transverse steel, to the fibers or to the pressure applied externally were shown.

INTRODUCTION

Numerous experimental and analytical studies mentioned in ACI Committee 544 [1] carried out on the behavior of fiber reinforced concrete (FRC) have shown that the addition of fibers to concrete matrices improves most of the mechanical properties of concrete: compressive strain, tensile maximum stress and corresponding strain, energy absorption capacity and toughness, shear resistance, fatigue strength, and crack distribution. In the case of normal weight or light weight high strength concrete [2] fibers in combination with traditional steel reinforcements reduce the brittleness characterizing these advanced materials. Fibers improve ductility of concrete and avoid congestion of secondary reinforcements required in critical regions of structures designed in seismic zones. Lightweight concrete, which was largely utilized for its non-structural properties (as lagging or sound-proofing material), has also been employed more recently to make structural elements, in particular in the field of precast concrete structures. Maintaining an adequate strength level, lightweight concrete, with respect to normal weight concrete, among other things permits a reduction in the horizontal inertia actions on structures in seismic regions, exerts a favorable effect on the foundations of buildings supported by soil having low bearing capacity, and facilitates the carriage of precast concrete elements. The physical and mechanical properties of lightweight concrete greatly depend on the aggregates, and in particular on their density: in general, greater aggregate density improves the strength of the material to the detriment of the non-structural

[1] Associate Professor, DISeG, Università di Palermo, Italy. Email: campione@stru.diseg.unipa.it
[2] Ph.D, DISeG, Università di Palermo, Italy. Email: cucchiar@stru.diseg.unipa.it
[3] Full Professor DISeG, Università di Palermo, Italy. Email: lamendol@stru.diseg.unipa.it
[4] Full Professor DISeG, Università di Palermo, Italy. Email: papia@stru.diseg.unipa.it

properties mentioned above. For lightweight concrete the use of fibers is suitable [3,4], also coupled with traditional steel reinforcements, because it reduces material decay in the field of the strains exceeding those corresponding to the strength. Complete knowledge of lightweight concrete properties and of the bond and anchorage characteristics is essential for evaluating the structural response and behavior under monotonic and cyclic loads [5-8].
In the present research experimental results of the local bond stress-slip relationship of reinforcing bars embedded in lightweight fiber reinforced concrete with expanded clay aggregates are presented.

EXPERIMENTAL PROGRAM

The aim of the research was to investigate the local bond-slip behavior of deformed steel bars embedded in lightweight fibrous concrete under monotonic and cyclic reversal loads. The parameters investigated were: - the confinement pressure acting perpendicular to the slippage direction of the bar; - the percentages of fibers; - the geometrical ratio of transverse steel confining the longitudinal bar.

Specimen geometry

Specimens used for the bond-slip tests had the geometry and dimensions shown in Fig. 1. The steel bar was embedded in the prismatic specimen in horizontal position, perpendicular to the direction of casting. Only the central part of the steel bar was bonded to the concrete, excluding contact with the concrete in the end portions of the specimen.

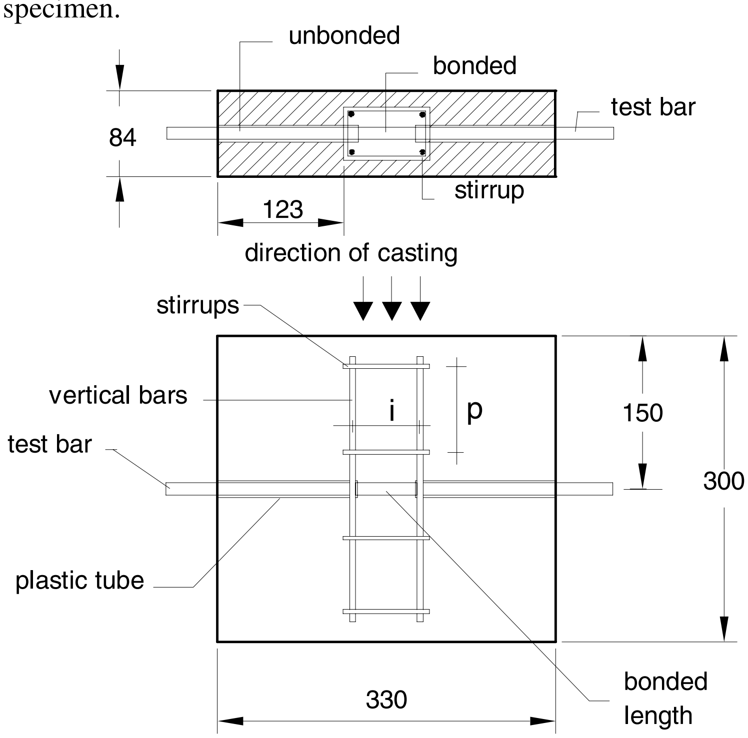

Figure 1. Test specimen

The choice of the specimen geometry, of the arrangements in the transverse steel and of the position of the embedded steel bar are intended to reproduce the condition of the main steel bars of a beam in the confined joint regions of concrete frame structures, as has already been done in a similar investigation [9] referring to ordinary concrete of normal weight and normal strength.
Moreover, in the absence of transverse steel, the dimensions assumed for the concrete specimen in relation to the position of the steel bars allow one to produce a split failure type. Form the same batch cylindrical specimens were also cast to characterize the material mechanically.

Concrete specimens were prepared varying the geometrical ratio of the transverse steel and the percentage of fibers. Two specimens were prepared for each series investigated. In the case of transverse steel bars closed stirrups made of steel wire having diameter 4 mm were placed as shown in Fig. 1 and in Fig. 2. Stirrups were fixed to main bars constituted by four deformed bars having 6 mm diameter and placed at a distance i of 72 mm. Stirrups were placed at pitches p of 32, 46, and 80 mm, respectively.
A deformed steel bar having equivalent diameter d_b = 12 mm and embedded in concrete for a fixed length of 60 mm (equivalent to 5 d_b) was utilized for the pull-out test. This anchorage length, as suggested in [9], is short enough to assume that the slippage recorded is representative of a local bond stress value.

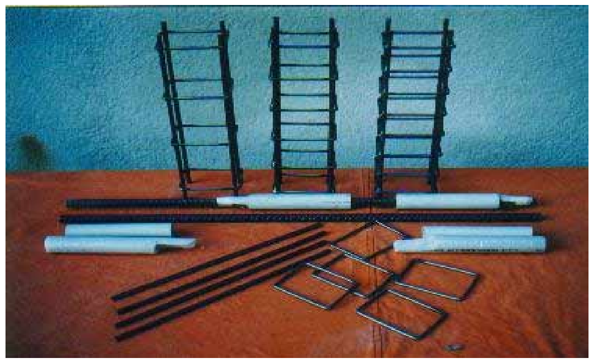

Figure 2. Arrangements of transverse and test bars

As already stated, the embedded length of the steel bar was only a reduced portion of the entire length of the bar placed in the specimens. It was possible to isolate the end portions of the bar during the casting process by using plastic tubes externally fixed to the steel bars and by placing layers of sponge between the steel bars and the plastic tubes.
Fig. 3 shows a view of the steel moulds utilized with the steel bars and the transverse steel inside before casting of the concrete.
Concrete was cast into the steel moulds and it was vibrated by means of a needle vibrator. After a curing period of 28 days in a room at constant temperature and humidity, the specimens were tested.

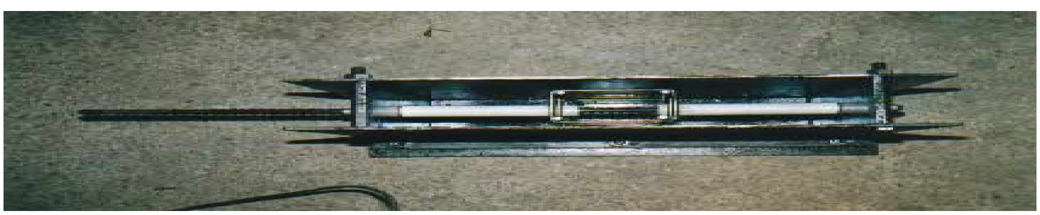

Figure 3. Photo of specimens prior to casting

Material proportions and mechanical properties
Lightweight concrete with expanded clay aggregates was utilized to prepare specimens. A very light concrete (weight density 1600 daN/m^3) with high cylindrical strength (34 MPa) was obtained by using the following components in daN/m^3: 350 of Portland Cement type 42,5 MPa, 490 of expanded clay with maximum grain size 12 mm (weight density of 650 daN/m^3), 780 of sand and 135 of water.
The total quantity of water was 205 daN/m^3, 70 daNg/m^3 of which was the content of water absorbed by aggregates left in a tank full of water for 30’, and 135 daN/m^3 the quantity of water added to the fresh concrete.
To prepare the fibrous concrete, hooked steel fibers having an aspect ratio of 60 were added to fresh concrete in a percentage v_f by volume of 0.5 and 1 % corresponding to 40 e 80 daN/m^3.
For the mechanical characterization of the concrete, direct compressive tests and indirect split tests were carried out on three cylindrical specimens for each type having diameter 100 mm and height 200 mm.

Tests were performed using a universal testing machine operating in a controlled displacement mode recording the complete load-deformation curves, not given here for brevity.
The experimental results relative to the compressive tests show that the presence of fibers does not change the maximum strength values, while it ensures better performances with respect to plain concrete (very brittle because of the nature of lightweight aggregates), especially referring to post-peak strength and the ductility resources.
In tension, as shown by the splitting tests, the presence of fibers in concrete ensures better performance with respect to plain lightweight concrete both in term of maximum and residual strength.
More details of mechanical properties are given in [5] relating to extensive experimental research on the general mechanical properties of lightweight fibrous concrete having the same characteristics as the concrete utilized in the present investigation.
Table 1 gives the maximum compressive strength values f_c' and the maximum tensile strength values f_t' both expressed in MPa, with variation in the volume percentage of fibers.

Table 1. Concrete compressive and tensile strength

v_f	f_c'	f_t'
0	34.4	2.26
0.5	34.9	3.32
1.0	35.4	3.65

The lightweight concrete type utilized is characterized by high strength values in relation to the weight density obtained and the type of aggregate utilized, and for this reason it can be classified as a high performance concrete.
For the mechanical characterization of steel bars direct tensile tests were carried out using the same testing machine as for testing concrete. Three specimens for each diameter were tested in tension. For the 12 mm bars a yielding stress f_y and ultimate stress f_t values of 513 MPa and 597 MPa were recorded, while for the 4 mm bar the yielding and ultimate stresses were 620 MPa and 700 MPa, respectively.

Test set-up

Pull-out tests were carried out by extracting the deformed bar of 12 mm diameter from the concrete block specimen. The free extreme of the bar was connected to the grips of the universal testing machine utilized for direct tensile tests on steel bars, while the part of the bar embedded in the concrete block was fixed, though a rigid steel frame, to the fixed part of the testing machine.
A controlled displacement test was carried out at a fixed displacement rate of 0.5 mm /min, and the reactive load and the corresponding slippage of the steel bar were recorded.
Fig. 4 shows a view of the test set-up utilized to perform pull-out tests.
Fig. 5 shows the geometry and the dimensions of the steel frame designed to fix the concrete specimens to the basement part of the testing machine. It consists in four threaded steel bars connected to two steel plates.
The upper one is a square steel plate stiffened by transverse steel plates and it is pierced in the central part allowing the steel bar to be fixed to the special grips of the testing machine.
The lower part of the frame is constituted by two steel plates, the lower one of which is fixed by means of a threaded nut to the fixed part of the testing machine and the second one at a distance of 160 mm from the previous one. This makes it possible to connect the lower and the upper plates through the threaded bars.

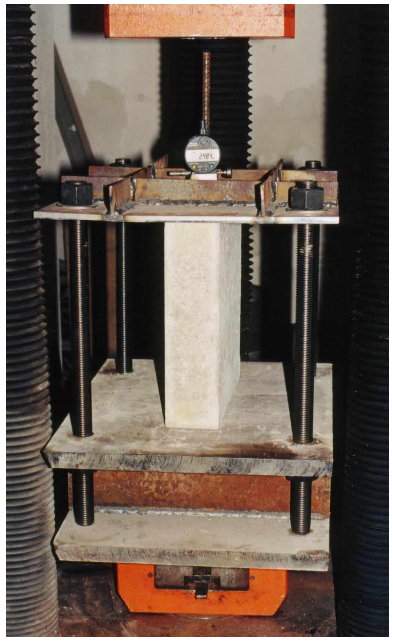

Figure 4. Photo of test specimen prepare for a tension test

As already mentioned, some specimens were also tested in the presence of external transverse confinement pressure induced by a special set-up shown in Fig. 6. It consists in a rigid steel frame made of four threaded bars connecting two stiffened steel plates. Between the two plates specimens were inserted with the direction of the embedded bar perpendicular to the steel frame. Moreover, on one side of the specimens a stiff steel plate was inserted and between this and the plate of the steel frame a hydraulic jacket having 20 kN bearing capacity was inserted. A spherical joint between the jacket and the plate reduces the effect of undesirable eccentricity.

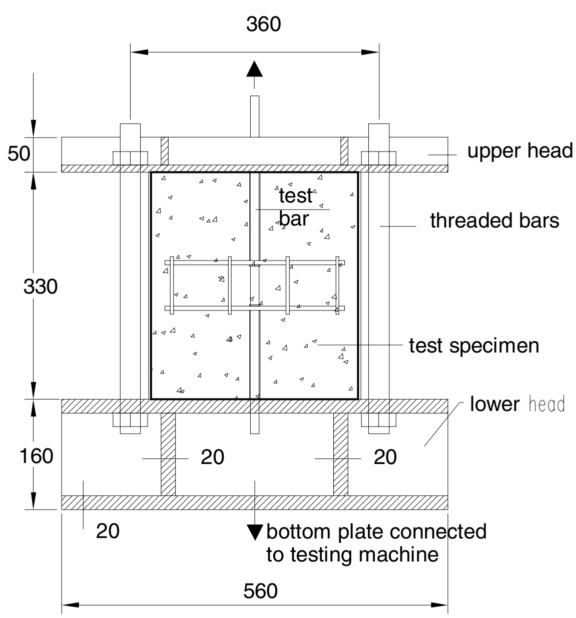

Figure 5. Test set-up

During the test, through a manometer it was possible to control the confinement pressure induced by the hydraulic jacket and a constant value of stress equal to 3.4 MPa (approximately equal to 10% of the compressive strength of lightweight plain concrete) was assumed.
To record the complete load-slippage curves a load cell coupled with a high speed data acquisition system was utilized. The slippage was recorded by means of an LVDT placed on a gauge length of 10 mm. The LVDT was mounted on special steel rings fixed on one side on the steel bar and on the other side on the upper part of the steel plate of the reaction frame. In this way it was possible to measure the slippage on a small gauge length, reducing the influence of extraneous deformations, and this made it possible to assume the slippage as a local measurement hypothesis also confirmed by the circumstance that steel behaves elastically during the pull-out process. Monotonic and cyclic reversal loading tests were carried out.

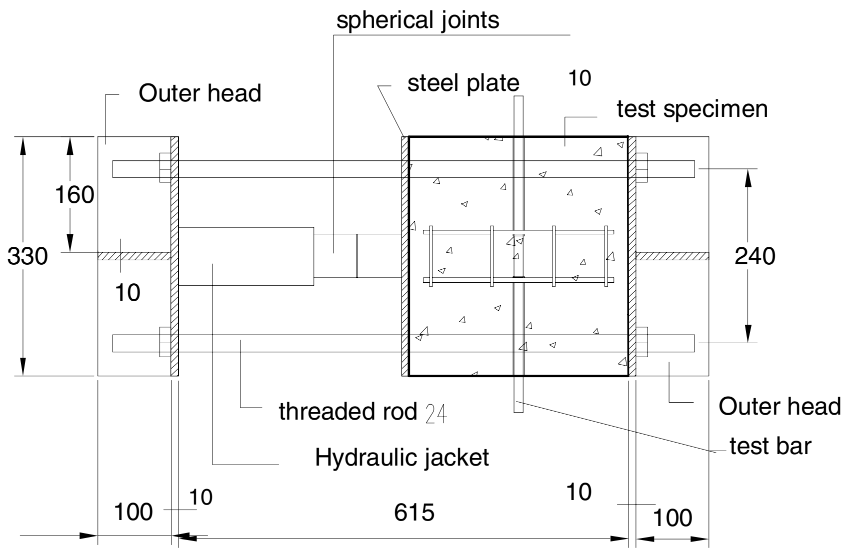

Figure 6. Device for applying transverse pressure

In the case of monotonic tests the steel bars were pulled-out from the specimens until the residual friction strength was reached.
In the case of cyclic reversal loading tests the bars were pushed-out and pushed-in for fixed values of slippage or for rising slippage values, with the aim of estimating the strength degradation due to the cyclic action.

EXPERIMENTAL RESULTS

The experimental results of the local bond stress-slip tests in terms of curve τ-s are presented for monotonic and cyclical loading conditions.
The bond stress-slip diagrams were deduced by taking the applied forces at given strip values and converting them into bond stresses using the equation: $\tau = \frac{F}{\pi \cdot d_b \cdot l_{anc}}$, F being the reactive force measured and l_{anc} the embedded length.
The slip s was detected as already indicated in the previous section. For all the specimens subjected to tests, the measured value of the slip force was normalized with respect to the compressive strength f'_{co} of the plain concrete equal to 34.4 MPa by means of the normalization criteria presented in [9]. The same normalization criteria were also used in [6,7] referring to pull-out tests on fibrous concretes.

The graphs of the monotonic tests given here refer to the middle curves of the two specimens for each typology, while those relating to the cyclical tests refer to one of the two specimens tested.

Monotonic loading

Fig. 7 shows a comparison between the bond stress-slip curves of the present research referring to plain lightweight concrete and the analogous ones obtained in [10] referring to pull-out tests carried out on specimens made of concrete having the same characteristics, with a bar of the same diameter and length embedded, but relative to concrete squat specimens having dimensions 170x170x210 mm for which pull-out rupture was found.

In the present research the strength value for pull-out resistance was less than that obtained in [10] showing that splitting failure occurs.

Form the graph in Fig. 7 it emerges that the initial stiffness of the bond stress-slip curve decreased gradually from its initial large value (the latter corresponding to chemical adhesion), to zero when approaching the maximum bond strength τ_{max} corresponding to a slip value of approximately 1.25 mm in which splitting failure with crushing cracks appears. After passing the maximum bond strength value τ_{max}, the bond resistance decreases slowly and almost linearly until it approaches a slip of 6÷7 mm, and then the next value corresponds to the distance between the drowned ribbings of the deformed bar in the concrete. For greater sliding values (7÷10 mm) the resistance decreases very slowly and its value approaches frictional resistance.

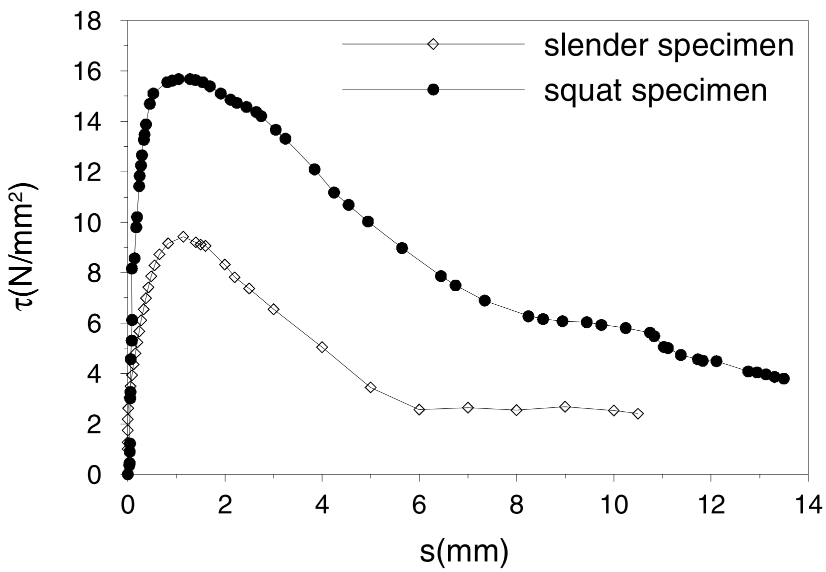

Figure7. Bond stress-slip relationship for test on plain lightweight concrete

From the examination of the experimental results it is possible to identify the following phases of the interaction between steel and concrete:

- initial phase of chemical adhesion in which there is reduced sliding between bar and concrete and the correspondent tension value τ is less than 1.2 MPa, (approximately equal to 3.5% of the cylindrical strength f_{co}');
- sliding phase in the presence of elevated local pressures between ribbings and concrete and formation of the first transversal cracks, but without appreciable interlocking of aggregates between the ribbings;
- crack formation phase with τ increased up to 1.2 ÷ 1,5 f_{ct} and transversal cracks form with consequent radial push on the concrete around the bar;
- stabilization of the crack pattern, and increase in their depth up to a bond stress level of 9 MPa (5÷6 times f_{ct}) beyond which the consequence of the split failure is the rapid drop in the load up to attainment of a residual bond stress of approximately 3 MPa.

As already stated, the pull-out of the bar was caused by cracking of a splitting type in the surrounding concrete, and the stress in the bar was lower than the maximum tension in the bar corresponding to the yield stress $f_y = 513$ MPa. It is interesting to observe that in the case of greater dimensions of specimens (see [10]) failure was manifested by pull-out of the steel bar with obvious interlocking of the aggregates, as can be seen from the greater peak strength values compared to those in the current test.

Fig. 8 shows the bond stress-slip curves for specimens of lightweight plain concrete in the presence of transverse reinforcement.

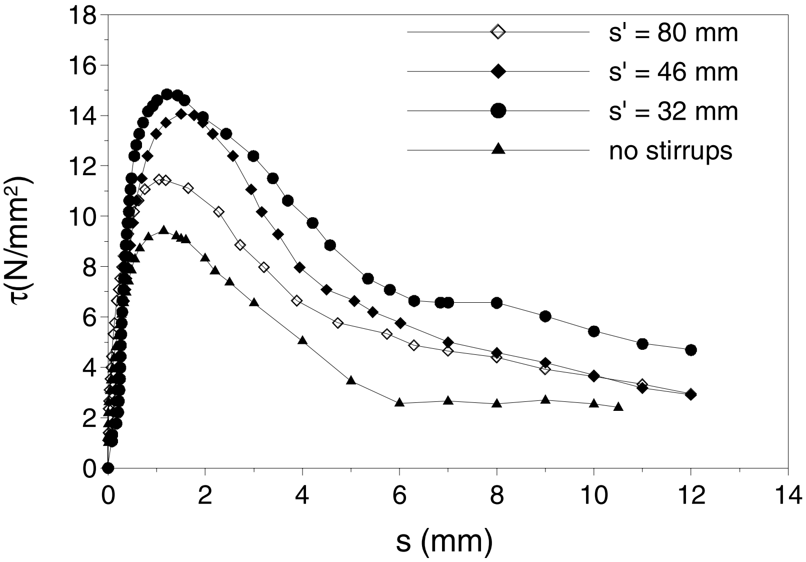

Figure 8. Bond stress-slip relationship for embedded bar in lightweight concrete with transverse steel

The experimental results obtained show that the features of the curves are analogous to those of the specimens without transverse reinforcement, especially in the ascending branch. The remarkable advantages in terms of increase in peak bond stress are very evident in the specimens with stirrups at pitches of 32 mm for which the increase in strength was very high with respect to the case of plain concrete and this increase in strength allows one to change the mode of failure from splitting to pull-out. This is explained by the fact that when the splitting cracks tend to form they are arrested by the stirrups. Moreover, the presence of stirrups at pitches 32 mm increases the residual strength value compared to plain concrete up to 30%. In the other cases (pitches 48 and 80 mm) the presence of stirrups does not make it possible to produce pull-out failure and splitting failure occurs. Table 2 gives the characteristic values of bond strength τ_{max} and of the corresponding slippage s_{max} with variation in the pitches of the stirrups. Moreover, the bond stress $\tau_{res}(s = 6\text{mm})$ measured at slippage of 6 mm is given as a measurement of residual frictional strength.

Table 2 Bond resistance for monotonic loading test

Pitch p [mm]	s (τ_{max}) [mm]	τ_{max} [MPa]	τ_{res} (s = 6 mm) [MPa]
32	1.21	14.84	7.00
46	1.50	14.05	5.75
80	1.05	11.44	5.00

Fig. 9 shows the bond stress-slip curves for embedded bars in lightweight fibrous concrete with variation in the volume percentage v_f of fibers (0.5 % and 1.0 %). The results obtained show that the addition of fibers has a negligible influence on the increase in the ultimate strength and on the overall response compared to the case of plain concrete.

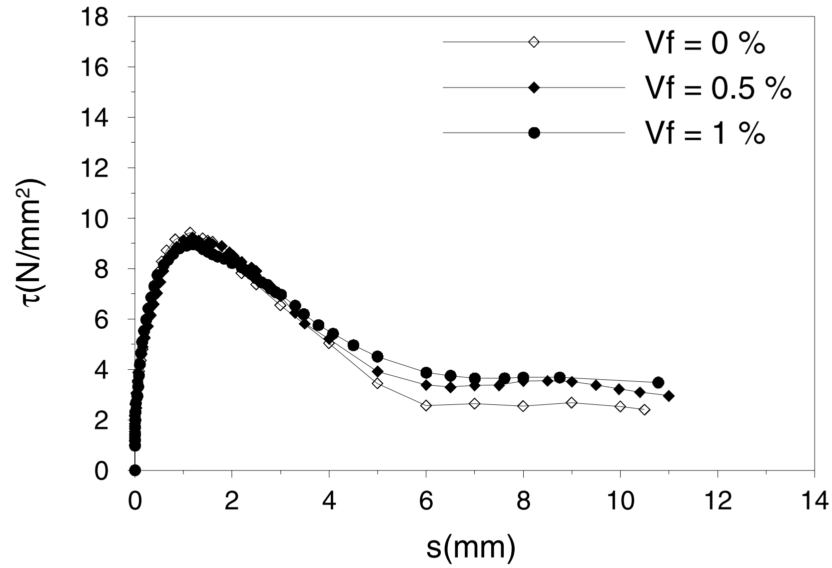

Figure 9. Bond stress-slip relationship for embedded bar in lightweight fibrous concrete

Table 3 uses the same symbols as Table 1, but refers to the case of a steel bar embedded in fibrous concrete.

Table 3 Bond resistance for monotonic loading test

V_f [%]	s (τ_{max}) [mm]	τ_{max} [MPa]	τ (s = 6 mm) [MPa]
0	1.14	8.42	2.53
0.5	1.18	9.25	3.38
1.0	1.19	8.97	3.68

Fig 10 shows the bond stress-slip curves relating to the cases of specimens externally confined by transverse pressure producing a stress on the lateral surfaces of the specimens equal to 3.4 MPa.

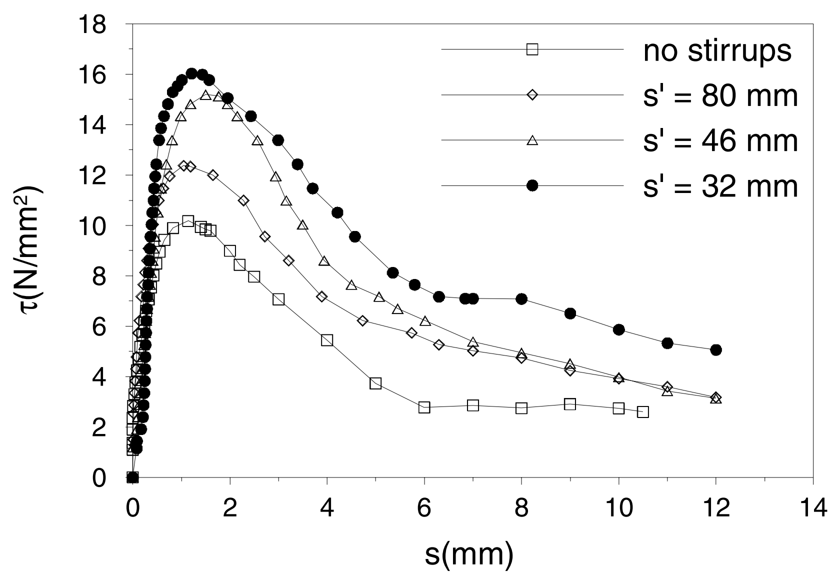

Figure 10. Bond stress-slip relationship for embedded bar in lightweight concrete with transverse steel and in the presence of confinement pressure

The experimental results show that the presence of confinement pressure slightly increases the maximum and the residual strength compared to the case of specimens without confinement pressure, also confirmed by [9], while in the presence of fibers and of confinement pressures no differences were observed compared to the analogous cases and in the absence of confinement pressure.
Table 4 uses the same symbols as Tables 2 and 3, but refers to the values of tests on specimens with stirrups and confinement pressure.

Table 4 Bond resistance for monotonic loading test

Pitch s' [mm]	s (τ_{max}) [mm]	τ_{max} [MPa]	τ (s = 6 mm) [MPa]
32	1.19	16.02	5.30
46	1.50	15.18	3.40
80	1.03	12.35	3.58

Fig. 11 shows the conditions of half of one specimen after failure. The portion of the concrete corresponding to the embedded length was crushed and interlocking of aggregates occurred at the interface.

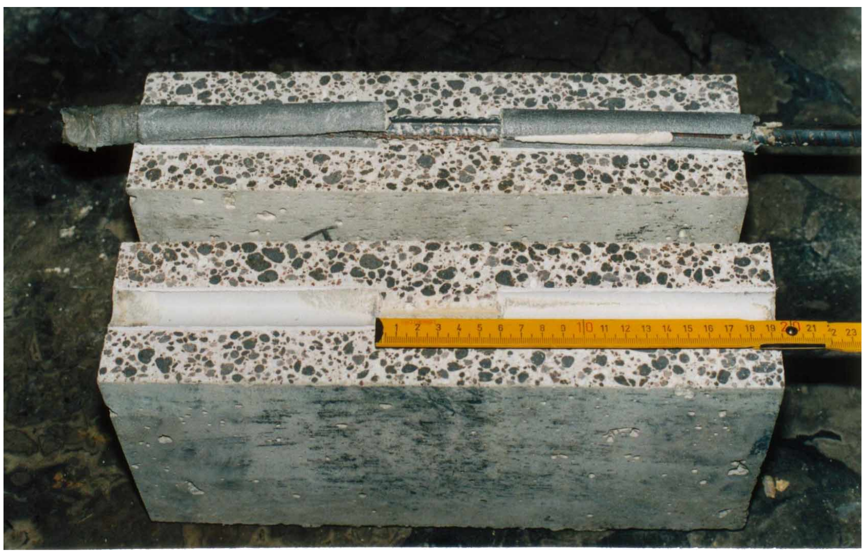

Figure 11. Photo of specimens with failure by splitting

Cyclic loading
The results of cyclic tests given in this section refer to the case of reversal loading and unloading of specimens with an increase in the maximum slippage assumed. Tests were carried out by unloading the specimens after the peak load was reached at a conventional stress of 0.8 of maximum strength.
The same parameters as investigated in monotonic loading are here examined for the cyclic case.
Fig. 12 shows the bond stress-slip curves under cyclic loading for embedded bars confined by transverse stirrups. Only cases more significant of pitches of 46 and 32 mm are given.
From the examination of the curves it emerges that the degradation of the bonding strength increases with the number of cycles in relation to the slippage reached before the reloading phase.
The experimental results show that the highest degradation in maximum strength occurs at the first cycle corresponding to attainment of the maximum shear strength of the concrete enclosed between two successive ribs. In the ensuing cycles, the concrete across the bar is locally crushed in compression and there is a reduction in the bond strength and in the frictional values.

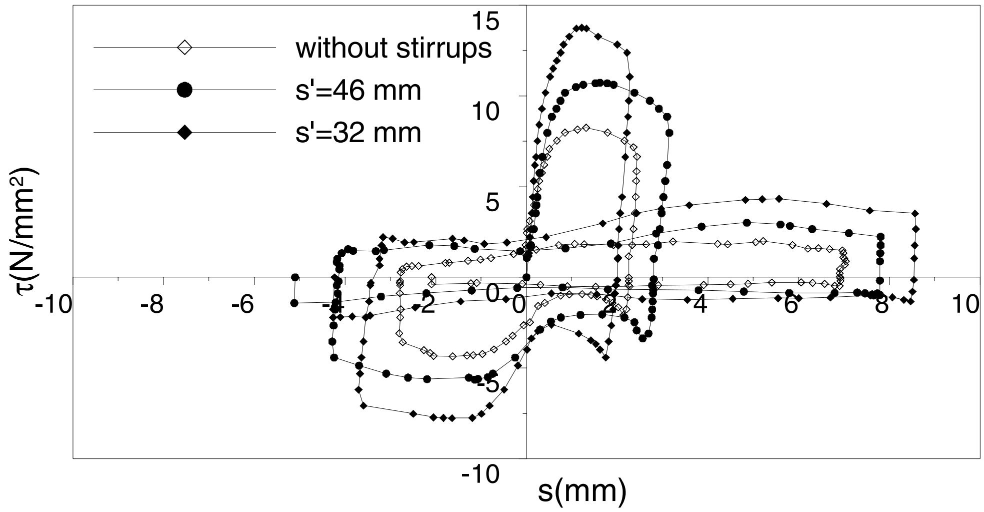

Figure 12. Cyclic bond-slippage curves for deformed bar embedded in specimen with transverse steel

Fig. 13 shows the effects of confinement pressure on the cyclic response of a bar embedded in lightweight concrete and confined with transverse stirrups. It is evident that the influence of confinement pressure is very reduced, a finding also confirmed in [9] for normal weight, normal strength concrete.

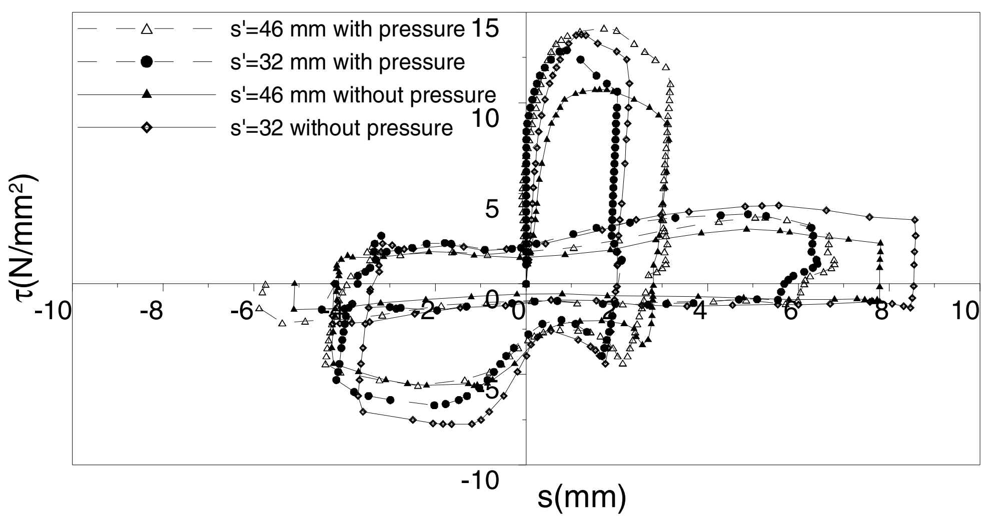

Figure 13. Cyclic bond-slippage curves for deformed bar embedded in specimen with transverse steel and confinement pressure

Fig. 14 a), b) and c) gives bond stress-slip curves relating to fibrous concrete. From the results it emerges that the cyclic response envelope follows the monotonic one (given in the same graph for comparison) and the presence of fibers does not exhibit a significant effect the cyclic case either, a circumstance already observed in [7]. It is possible to observe that for all cases examined after the peak load is reached the softening branch is governed by the pull-out process depending on the number of cycles, a phenomenon well known in the case of normal weight, normal strength concrete [9], with the difference related to the major brittleness of the lightweight aggregates utilized. Referring to the case of fibrous concrete, not given here for brevity, no variations in terms of maximum or residual strength were observed.

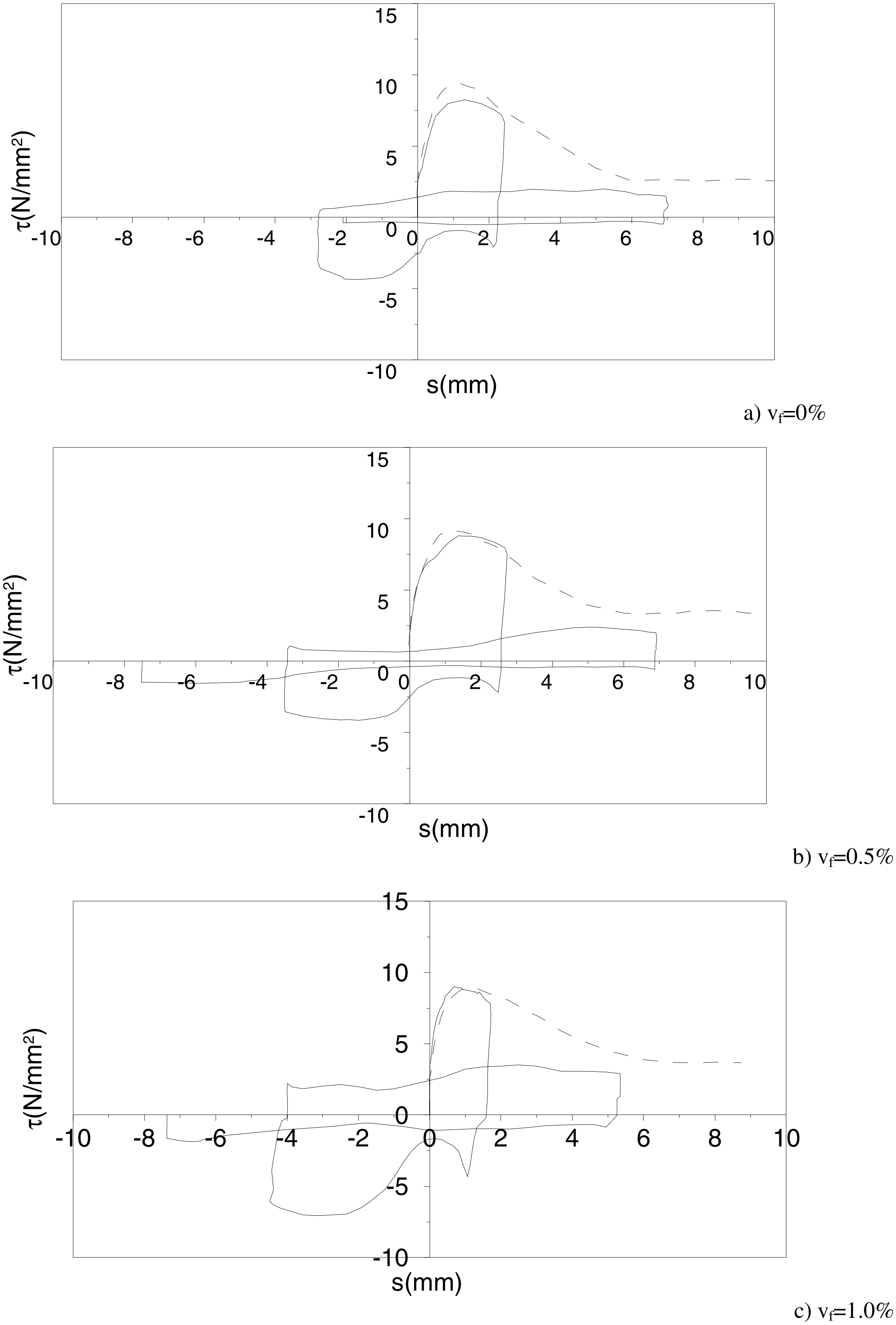

Figure 14. Local bond stress-slip relationship for deformed bar embedded in fibrous lightweight concrete under cyclic loading

CONCLUSIONS

Experimental results of local bond stress-slip tests on reinforcing bars embedded in lightweight fiber reinforced concrete with expanded clay aggregates were presented. For fixed diameter of steel bar and confinement external transverse pressure value, the effect of different percentages of hooked steel fibers and different geometrical ratios of transverse reinforcement was investigated.

Experimental results obtained regarding the behavior of material showed that although lightweight concrete is characterized by brittle behavior it is possible to achieve the ductility required for seismic purposes by using adequate percentages of short fibers or by transverse confinement induced by closed stirrups. Regarding the bond-slip behavior of embedded reinforcing bars it was shown that the interaction phenomena are essentially the well-known ones observed for normal weight concrete with a fundamental difference regarding the brittle nature of lightweight aggregates governing the maximum and frictional strength values.

Referring to monotonic pull-out tests it was observed that the presence of stirrups in rising geometrical ratios produces increases in maximum and residual frictional strength and in some cases also changes the failure mode from split to pull-out. Using fibers only moderate effects in term of maximum and residual strength increases were observed.

Under cyclic action the deterioration in stiffness and in maximum strength is not influenced by the presence of stirrups or fibers, highlighting the brittleness of the aggregate during the interlocking phenomenon. Using stirrups in the direction perpendicular to the pull-out direction it is possible to increase the residual strength while in the presence of confinement pressure (for the only value examined) no benefits were observed under both monotonic or cyclic reversal actions.

REFERENCES

[1] ACI Committe 544, "Design considerations for steel fiber reinforced concrete", *ACI Structural Journal* (1988);85(5): 563-580.

[2] Campione G., Mindess S., and Zingone G., "Compressive stress-strain behavior of normal and high-strength carbon-fiber concrete reinforced with steel spirals", *ACI Materials Journal* (1999); 96(1): 27-34.

[3] Balaguru P., Foden A., "Properties of fiber reinforced structural lightweight concrete", *ACI Structural Journal* (1996); 93(1): 62-77.

[4] Campione, G. Miraglia, N. and Papia, M., "Mechanical properties of steel fiber reinforced lightweight concrete with pumice stone or expanded clay aggregates", *Materials and Structures*,(2001); 34(238): 201-210.

[5] Ciampi V., Eligehausen R., Bertero V.V., Popov E.P., "Analytical Model for Deformed Bar Bond Under Generalized Excitations" IABSE Colloquium on "Advanced Mechanics of reinforced Concrete", Final Report, Delft, December (1981): 53-67.

[6] Harajli, M., "Local bond-slip behavior of reinforcing bars embedded in fiber reinforced concrete", Procedings, International Conference, Bond Concrete-From Research to Practice, Comitè Euro International du Bèton, Riga, Latvia, (1992):87-96.

[7] Harajli M., Hout M., Jalkh W., "Local bond stress-slip behavior of reinforcing bars embedded in plain and fiber concrete", *ACI Materials Journal*, (1995);4(1):343-353.

[8] Hota, S., Naaman, A., "Bond stress-slip response of reinforcing bars embedded in FRC matrices under monotonic and cyclic loading", *ACI Structural Journal*, (1997);4(5):525-537.

[9] Eligehausen R. , Popov E.P. and Bertero V.V.,"Local bond stress-slip relationship on deformed bars under generalized excitations" Report N.O.UCB/ERC-83/23 (1983): 1-168.

[10] La Mendola L. and Papia M.," Legame locale di aderenza acciaio-calcestruzzo leggero fibrorinforzato", Atti delle Giornate 13 Convegno AICAP (2000), 2: 393-402 (only in italian).