Experimental behavior of fiber concrete slabs on soil

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Summary

The cracking control of plain concrete slabs on soil foundation requires the execution of joints with mechanisms of load transfer between adjacent panels. These joints increase the construction costs and, often, are the source of local damage and loss of service performance. Slabs reinforced with steel wire mesh have been used in order to increase the load carrying capacity and to enhance the cracking control. However, the use of this conventional reinforcement increases the costs, mainly due to labor time spent on the arrangement and positioning of the reinforcement.

Fiber reinforced concrete is a recent material well fitted for applications in industrial floors on soil foundation. The cost of fibers is compensated by a faster construction process and a reduction in the number of expansion joints. The fatigue, impact and flexural strength are significantly improved when steel fibers are added to the concrete mix.

The work developed aims to contribute to the on going research effort to clarify the behavior of fiber reinforced concrete slabs on soil foundation. For this purpose, an experimental and numerical investigation were carried out. The present article deals basically with the experimental work developed, describing the tests performed and discussing the main results obtained.

KEY WORDS: experimental analysis; slabs on soil; reinforced concrete; steel fibers; fracture energy

1 - INTRODUTION

All published research work[1,5] has corroborated that the addition of steel fibers to concrete considerably improves the toughness and the resistance to dynamic, cyclic and impact loads, and reduces the crack width and spacing. The degree of improvement depends on the type and aspect ratio (length to diameter ratio) of the steel fibers. It has been shown[1] that hooked-ends steel fibers glued together side by side into bundles with a water solvable glue perform better in fresh concrete, improving the mix workability and eliminating balling[4]. This type of fibers are also more efficient than straight steel fibers in improving the mechanical concrete properties[5]. Thus, hooked-ends steel fibers were selected to be used in the present research program.

Industrial floors are the type of structures wherein the application of steel fiber reinforced concrete (*SFRC*) is advantageous[6,7,8]. During the service life these structures are subjected to cyclic and impact loads, requiring an adequate fatigue flexural strength and energy absorption capacity. *SFRC* has also been economically competitive in industrial floors, when compared with conventional reinforced concrete, since it eliminates the time needed to place the mesh reinforcement and to keep it in position during concrete casting. In comparison to plain concrete (*PC*) solution, *SFRC* pavement can be 30-40% thinner, resulting in further savings.

In order to assess the effectiveness of steel fibers as a substitute of the conventional reinforcement in slabs on soil foundation and to evaluate the benefits of fiber concrete over plain concrete in these applications, an experimental program was developed. This article is devoted to describe the experimental tests and to discuss the main results obtained. These results will also be used to appraise a numerical model developed for the nonlinear analysis of reinforced concrete structures.

2 - DESCRIPTION OF THE TESTS

The experimental program consists of two series of tests. Each series includes two slabs reinforced with hooked-ends steel fibers (30 kg/m^3 and 45 kg/m^3 of *ZX60/.80* Dramix fibers[9]), one slab reinforced with wire mesh placed in the tensile face (A_{sx}=A_{sy}= 94 mm^2/m, corresponding to 20 kg/m^3 of a steel with yield and ultimate strength of 560 MPa and 700 MPa, respectively), and one plain concrete slab.

Figure 1 shows schematically the structure supporting the test set up. It consists of HEB 300 steel profiles, setting up a frame which offers reaction to the actuator, and a platform which supports a timber box filled with the soil.

Figure 2 shows a schematic representation of the equipment for load application and data acquisition employed in tests. The load was supplied by a hydraulic actuator to which a load cell with a maximum capacity of 1000 kN was attached. Displacements were measured with *LVDTs* (Linear Variable Differential Transducers) attached to a grid frame fixed to the exterior of the supporting structure. The load application was automatically controlled, once the loading path was defined. It was applied a loading rate of 2.5 kN per minute. The measurements were registered every five seconds.

The soil was initially compacted with a mechanical device currently employed in practice. After each test, the soil under the loaded area was removed, replaced and recompacted.

The slabs were cast in a timber mold, faced with a zinc plate, and were compacted with a vibrating ruler. During the first seven days after casting, the slabs and the corresponding cylinder and prismatic specimens were covered with wet cloths. Then, the slabs and the specimens were kept in the natural environment of the laboratory (65% RH and 20°C) until the date of testing. Five days before testing, the soil was covered with a polyethylene sheet, over which a layer of cement mortar with about 5 mm of thickness was spread, where the slab was settled. In this way, a uniform contact between slab and soil was warranted and the friction soil-slab was reduced. The slabs were not molded against the soil, such as in practice, in order to increase the frequency of the tests.

3 - MATERIAL PROPERTIES

3.1 - Concrete

The mixture proportions used for the slabs are specified in Table 1. For each slab, at least two prismatic specimens of dimensions 600x150x150 mm^3 and two cylinders of 150 mm diameter and 300 mm height were tested, in order to assess the flexural and compression concrete behavior, respectively. The main results obtained are presented in Table 2. The fracture energy is evaluated from RILEM recommendations[10]. The energy supplied by the weight of the beam was taken into account[11]. The flexural toughness factor is determined from the method proposed by JSCE-SF4[12] and is defined as the energy required to deflect the beam to a midpoint-deflection of 1/150 of its span (450 mm).

3.2 - Soil

In order to approximate the support conditions to those of slabs on soil, a 550 mm thickness layer of soil with the properties and characteristics presented in Table 3 was employed.

Control tests were made on the soil layer before performing the slab tests. The compactation moisture content and the degree of compactation were about 16.5% and 90%, respectively.

To evaluate the soil reaction modulus, plate loading tests were performed with a standard steel plate[15] (300 mm diameter and 25 mm thickness). The loading rate and the frequency of the scan readings were similar to those used in the slab tests. The soil pressure versus displacement curves obtained before the first and second series of slab tests are shown in Figure 3. The soil pressure (p_s) is the ratio between the force and the area of the loading plate. The displacement (δ_{av}) is the average of the values registered with three *LVDTs*. The $p_s - \delta_{av}$ relationship up to $p_s \cong 140\ kPa$ reproduces the soil behavior, characterised by a soil reaction modulus of approximately 70 MN/m^3. Beyond this pressure, the $p_s - \delta_{av}$ relationship represents the response of the system soil-soil container, exhibiting an approximate average reaction modulus of 125 MN/m^3 (see Figure 3). After $p_s \cong 500\ kPa$ a nonlinear relationship between p_s and δ_{av} is obtained, representing the soil-system nonlinear behavior.

4 - EXPERIMENTAL RESULTS

In Figure 4 the load-displacement relationship at *LVDT* number 1 (see Figure 2) is presented for all tests performed.

Figure 5 shows the load-displacement relationship at *LVDT* number 1 (see Figure 2) for each type of slab in both series of tests. The test of the slab reinforced with 45 kg/m^3 of fibers of the second series of tests (*SL2s45*) was accidentally stopped at 248 kN. Table 4 specifies the ultimate load and describes the failure mode of the slabs tested.

In Figures 6 and 7 the displacements measured with the *LVDTs* placed along the alignment A3 (see Figure 2) are illustrated, for the first and second series of tests, respectively, at five different load levels. The values measured by the *LVDTs* are marked. The thick line simulates the loaded area. Up to a load of approximately 100 kN, the loss of contact between slab and soil was only observed in the tests of the *PC* slabs. After this load, the sinking of the loaded area (zone circumscribed by a radius of approximately 0.4 m from the center of the slab) was followed by the loss of contact between slab and soil (see Figures 6 and 7).

After each test, the slabs were hold upright (which was not possible for the *PC* slabs because they were split in parts), the over layer applied to the bottom surface was removed and the crack patterns were highlighted. The crack patterns of the first and second series of tests are similar. Figure 8 illustrates photos of the crack patterns observed in the slabs of the second series of tests.

5 - DISCUSSION OF THE RESULTS

5.1 - Comparison between experimental and numerical results

In order to ascertain the structural behavior and some of the results obtained in the experimental analysis of fiber concrete slabs on soil, a numerical analysis of the slabs tested was carried out. Details of the computational code developed, the material parameters involved in the formulation and the discussion of the numerical results can be found elsewhere[16]. In this section a brief description of the model will be given and the response of the slabs is presented.

The model developed[16] for nonlinear analysis of bi-dimensional concrete structures reinforced with fibers and/or ordinary steel reinforcement is based on the strain decomposition concept for the cracked concrete zones[17,18]. According to this concept, cracked concrete is regarded as cracks and concrete between cracks, as it is schematically represented in Figure 9.

In this model, the total strain increment of cracked concrete, $\Delta\underline{\varepsilon}$, is the addition of the strain increment of the fracture zone, $\Delta\underline{\varepsilon}^{cr}$, with the strain increment of the concrete between cracks, $\Delta\underline{\varepsilon}^{co}$. From the finite element point of view the width of the fracture zone is the characteristic length[19] of the finite element over which the micro-cracks are smeared out. The concrete fracture mode I (D_I^{cr}) and mode II (D_{II}^{cr}) are directly simulated in the crack constitutive law. As this relationship is explicitly included in the formulation, the model allows the simulation of the fiber reinforcing effects in a direct way, namely the increasing in fracture energy and in shear stiffness. The shape of the softening diagram was determined from numerical simulation of three-point bending tests carried out on notched beams[20]. The nonlinear behavior of concrete between cracks is simulated within the framework of the theory of plasticity[16,17].

The slabs were discretized by 8-noded isoparametric shell elements. A layered approach was used to capture the material behavior through the slab thickness. The concrete shell element can be reinforced with layers of smeared steel. The elasto-plastic behavior of the steel reinforcement can be simulated by a multilinear or linear-parabola stress-strain relationship. The tensile behavior of the cracked concrete layers under the influence of the reinforcement[21] is simulated by using a tension stiffening model[16].

The soil has been simulated by equivalent springs orthogonal to the slab surface. The constitutive relationship of the springs (soil-soil container system) has been determined by fitting the $p_s - \delta_{av}$ relation obtained in the plate tests (see Figure 3). The possibility of the loss of contact between slab and soil is accounted for by the model.

The material parameters used in the analysis of the slabs are the average values obtained in the corresponding specimens of both series.

In Figure 10 the experimental and the numerical load-displacement of *LVDT* 1 (see Figure 2) relationships are illustrated. The results compare fairly well, showing that the experimental set up is free of unexpected effects which could give erroneous responses.

5.2 - Remarks on the results

From Figures 4 and 5 and from Table 4 it can be concluded that the addition of steel fibers to concrete significantly increases the load carrying capacity and the ductility of the slabs on soil.

Analysing the Figures 4 to 7 it can be observed that the behavior of the *PC* slabs is substantially different from the reinforced slabs. After cracking, at approximately 70 kN, the *PC* slabs lost the major part of its stiffness, due to the reduced energy absorption capacity of the plain concrete, and failed by punching (see Figure 8a). The steel fiber and the wire mesh reinforced concrete slabs cracked at about 100 kN. After this load the stiffness decrease of the *SFRC* slabs was smooth, due to the improvement of energy absorption capacity given by fiber reinforcement. Between first cracking and failure several cracks developed (see Figures 8b and 8c), and a rather ductile failure mode was observed in *SFRC* slabs. In slabs reinforced with wire mesh, the stiffness decrease after first cracking was similar to the *SFRC* slabs, however, a more concentrated crack pattern was observed (see Figure 8d) and near failure some wires crossing the cracks started to break. A more brittle failure mode was observed in these conventionally reinforced slabs in comparison to the failure mode of *SFRC* slabs.

The minimum area of reinforcement ($A_{s,\min}$) required within the tensile zone will be[21] $A_{s,\min} = 0.4 \times f_{ctm} / f_{sym} \times h/2 \times 1000 = 86$ mm^2/m, where f_{ctm}=3.2 MPa is the average concrete tensile strength, approximated from the results determined in the uniaxial compression tests ($f_{ctm} = 1.4\left(\left(f_{cm} - 8\right)/10\right)^{2/3}$ MPa), f_{sym}=560 MPa is the yield strength of the steel and *h* is the slab thickness. The $A_{s,\min}$ is slightly less than the reinforcement area used in the slabs with wire mesh ($A_s = 94$ mm^2/m). Taking into account that in industrial floors it is necessary to reinforce the top and bottom slab surfaces, it can be concluded that a slab reinforced with 30 to 45 kg/m^3 of fibers exhibits a behavior similar to a slab reinforced with twice the minimum area of flexural reinforcement.

6 - CONCLUSIONS

The load carrying capacity of the slabs on soil foundation is considerably increased when steel fibers are added to the concrete mix. In comparison to the plain concrete slabs, the slabs reinforced with 30 and 45 kg/m^3 of fibers, and the slabs reinforced with wire mesh in tensile face ($A_{sx} = A_{sy} = 94$ mm^2/m) developed an average ultimate load 49%, 60% and 64% higher, respectively. It must be also taken into account that the *SFRC* slabs have identical resistance under positive and negative moments, which is equivalent to slabs conventionally reinforced in both faces.

The cracking behavior is also improved by fiber reinforcement, developing a large number of thin cracks. The material durability is enhanced and the number of expansion joints needed is smaller. The ultimate behavior of the *SFRC* slabs was much more ductile than that exhibited by the plain concrete slabs.

Since the fracture energy is the material property most benefited by fiber reinforcement, it must be taken into account in the models used for the design of *SFRC* slabs on soil foundation.

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