Construction and Building Materials 23 (2009) 785–794

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Lateral load response of steel fiber reinforced concrete model piles in cohesionless soil

Gurkan Ozden [a,*], Cihan Taylan Akdag [b]

[a] Dokuz Eylul University, College of Engineering, Department of Civil Engineering, 35160 Buca-Izmir, Turkey
[b] Dokuz Eylul University, Graduate School of Natural and Applied Sciences, 35040 Bornova-Izmir, Turkey

ARTICLE INFO

Article history:
Received 1 December 2006
Received in revised form 2 March 2008
Accepted 3 March 2008
Available online 24 April 2008

Keywords:
Model pile
Steel fiber reinforced concrete
Lateral load
Sand

ABSTRACT

It has been long recognized that piles could be damaged under major lateral loading environments. Precautions such as increasing pile dimensions or reinforcement to avoid damages were often proved to be inadequate for satisfactory pile design especially against heavy lateral loads. This fact necessitated research for piles that are more resistant to lateral forces. Recent debate for better lateral load performance has been about the design and construction of ductile piles. In this respect, steel fiber reinforced concrete (SFRC) can be considered as a contemporary material being able to provide desired additional ductility to conventional reinforced concrete (RC) piles. The lateral load carrying mechanisms of SFRC piles and their interaction with surrounding soil have not been fully studied yet. In this study an investigation for lateral load carrying capacity of SFRC piles in cohesionless soils has been undertaken. A model study involving instrumented model piles, a testing pool and a monotonic loading mechanism has been planned and pursued. Three different steel fiber ratios by volume were utilized in the production of model piles. Performances of these piles were compared with that of the conventional concrete pile. The goal was to observe the influence of steel fibers on ductile pile behavior by isolating them from other reinforcement components (i.e. bending and shear reinforcement). It has been found that SFRC model piles with steel fiber reinforcement ratios of 1% and 1.5% are capable of providing more ductility and higher lateral load carrying capacity while taking lower bending moments compared with the concrete model pile.

1. Introduction

It has been noticed in the past that piles have faced damages under major lateral loads [1,2]. It has been demonstrated by previous observations that increasing pile dimensions or reinforcement may not be adequate for satisfactory pile design that are resistant to heavy lateral loads. This fact has triggered intensive research in the last two decades and resulted in better understanding of lateral load carrying mechanisms of pile foundations. Major improvements to design and analysis methods have been made in the past [3–6]. Knowledge accumulated during model and field test studies have played an important role in the development of new analysis methods [7–9]. Such research and past experiences revealed that use of more ductile piles have become a necessity since high pile curvatures are unavoidable for most cases. However, allowable inelastic action of such piles and their allowable ductility under lateral loading conditions, on the other hand, has not been fully studied yet and more research effort is needed on this subject [10].

In this respect, steel fiber reinforcement would provide the desired additional ductility to laterally loaded conventional reinforced concrete piles. Cementitious matrices such as concrete have low tensile strength and fail in a brittle manner [11]. Adding short needle-like fibers to such matrices enhances their mechanical properties, particularly their toughness, ductility and energy absorbing capacity under impact. The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Flexural strength, fatigue strength, tensile strength and the ability to resist cracking are also enhanced [12–14].

Although there are several reported case histories regarding use of steel fibers especially in high strength concrete applications such as structural repair works and bridge girders [15,16], it appears that steel fibers have not enjoyed a proportional popularity among practicing engineers and researchers as a reinforcing material in concrete piles. There are some reported SFRC pile applications supported by national regulations and research in France [17]. Buyle-Bodin and Madhkhan investigated ductility and energy absorbing capacity of SFRC piles under cyclic loading. They, however, tested the piles on simple supports without surrounding soil. SFRC piles have been utilized in the construction

* Corresponding author. Tel.: +90 232 412 7061; fax: +90 232 453 1192.
E-mail addresses: gurkan.ozden@deu.edu.tr (G. Ozden), taylan.akdag@deu.edu.tr (C.T. Akdag).

0950-0618/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2008.03.001

of flood protection wall of Horse Mesa Dam located in 100 km northeast of Phoenix Arizona [18]. An SFRC piled wall construction was proposed there in order to prevent washing out of the access road of the dam by discharge water. It was reported that SFRC piles performed successfully resisting impact loads due to debris flow.

Findings of a model study regarding lateral load carrying capacity of SFRC piles are presented herein. Modeling considerations, results and analyses of monotonic lateral load tests on SFRC model piles surrounded by a cohesionless soil layer in a testing pool are given and discussed. The SFRC piles as used in the tests were cast without any longitudinal reinforcement bars. Their performances were compared with that of a concrete model pile so that contribution of steel fibers to lateral load carrying capacity can be better observed and analyzed.

2. Characteristics of materials

Three types of materials including steel fibers, concrete, sand and gravel were utilized throughout the study. Hooked-end steel fibers were used in the production of SFRC piles. Poorly graded sand with some non-plastic silt content and well-graded gravel served as horizontal subgrade materials to the laterally loaded model piles. Performances of SFRC model piles under lateral loading were compared with that of the conventional concrete pile without reinforcement.

2.1. Model pile materials

Length, diameter and aspect ratio of the hooked-end straight steel fibers were set as 30 mm, 0.55 mm and 55 in the study, respectively. The aspect ratio is commonly defined as the ratio of fiber length to its diameter. The manufacturer of the fibers reported density and minimum tensile strength as 7.8 gr/cm^3 and 1100 MPa, respectively. This type of steel fiber is the smallest hooked-end fiber that can be safely used in small scale model SFRC piles since shorter fibers with aspect ratios less than 50 have been reported as not being able to interlock to the concrete matrix and easily dispersible by vibration [19].

Diameter of the model concrete and SFRC piles and steel fiber dimensions dictated concrete mix design. As explained in the following section, diameter of the model piles were set as 7 cm forcing the maximum aggregate size equal to 12.5 mm since it should not exceed one-fifth of the narrowest dimension of a structural element [20]. The size of the maximum aggregate also complied with the requirement that steel fiber length should be at least two times larger than the aggregate size. Gradation of the concrete aggregate, however, was based on the ACI-544.1R-8 criterion. The gradation curve of the aggregate mixture as used in this study is shown in Fig. 1. Respective values of the water/cement ratio and cement content of the conventional concrete and SFRC batches were set as 0.45 and 495 kg per cubic meter. Mixture proportion was established after necessary corrections for the target air content and slump were made during casting trial batches.

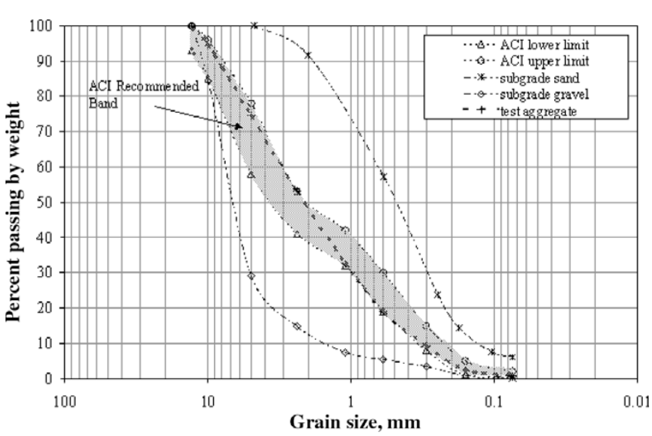

Fig. 1. Grain size distribution of the granular test materials.

Laboratory control tests including uniaxial compression, flexural strength, slump, inverted slump and air content determination were performed on the conventional concrete batch and the SFRC batch with a fiber content of 1.5% by volume to ensure that standard and repeatable concrete batch production could be made. The 20 cm long cylindrical samples with a length to diameter ratio of two and prismatic samples of $10 \times 10 \times 60$ cm in size were compacted by means of a vibration table. The uniaxial compression and third-point loading flexural strength tests were performed at standard testing rates of 2.35 kN/s and 0.2 kN/s, respectively. Variation of compressive and flexural strengths of the conventional and SFR concrete samples with curing time are given in Fig. 2a and b, respectively. It can be noticed in Fig. 2a that compressive strength of the SFRC is slightly less than that of the conventional concrete in early days of the curing period reaching to 41.05 MPa being almost equal to the strength of conventional concrete at 28 days indicating that addition of steel fibers to the concrete matrix does not provide a pronounceable benefit in terms of compressive strength. It shall be noted that comparison of compressive strengths of laboratory samples with those of the model pile samples did not show any significant scatter. Contribution of steel fibers to flexural strength, however, is clearly reflected in Fig. 2b. The flexural strength of the SFRC batch with 1.5% fiber has been consistently found to be 16% larger than that of the conventional batch samples on the average. Flexural strength values of simply supported model piles under constant moment loading, on the other hand, were less than those of the standard laboratory beam samples. The concrete pile and the SFRC pile with 1.5% steel fiber content yielded flexural strength values of 2.67 and 4.37 MPa, respectively. Both values are considerably less than the results of the third-point beam tests, the difference being 57% for the concrete pile and 39% for the SFRC pile. A closer look to the characteristics of the concrete revealed that model piles were not compacted to the same degree with beam samples since their length and diameter prohibited rod tamping. Instead model piles were compacted by means of a vibration table during concrete cast. The dry unit weight and water absorption of the SFRC model pile has been found as 21.97 kN/m^3 and 7.43%, respectively. Same parameters happened to be 22.96 kN/m^3 and 4.36% for the SFRC laboratory beam sample. It should also be noted that it was not possible to orient steel fibers along the length of the model pile in contrast to the laboratory samples where steel fibers were purposely aligned parallel to the longer axis of the beam using a hand tool. It has been previously stated that the coarse aggregate and the steel fibers tend to align perpendicular to the direction of casting resulting in occurrence of voids underneath these elements [21].

2.2. Subgrade materials

The soil surrounding the pile was artificially prepared in two layers. Layers were compacted by dry tamping method. The upper layer consisted of medium dense uniform silty sand whereas the underlying gravel layer was well-graded. The soil layers were in dry condition throughout the testing program. The sand layer served as the main subgrade material whereas the bottom gravel layer functioned as the dense soil providing necessary soil support to the pile so that the pile would not exhibit rigid body motion and occurrence of at least one plastic hinge was ensured while the piles were loaded to failure. Grain size and index characteristics of both sand and gravel are given in Table 1. The minimum median