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Dynamic Properties of Polypropylene Fiber-Reinforced Concrete Slabs

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Abstract

A series of experiments were performed on both simply supported and on-grade circular slab specimens, reinforced with different volumes of fibrillated polypropylene fibers, to gauge the fibers' influence on the slab's impact resistance and natural frequency. Numerical simulations were then used to reproduce the natural frequencies. In conjunction with these experiments, standard compression and flexural tests were run to determine the material strength of the concrete. It was found that the inclusion of fibers produced an improvement in impact resistance proportional to the fiber volume contained in the concrete and had no affect on the natural frequency. An inverse relationship between fiber volume and material strength was also found for both compression and flexure. © 1997 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

Fiber-reinforced concrete (FRC) consists of hydraulic cements with fine aggregates, coarse aggregates and discontinuous, discrete fibers that can be grouped into two categories: those with low modulus of elasticity and high elongation properties and those with high modulus of elasticity. Synthetic, organic fibers, such as nylon, polypropylene and polyethylene, belong to the first category, whereas steel, glass, asbestos and carbon fibers belong to the second one. Use of the former group of fibers does not lead to increase in strength, but does improve material toughness and resistance to impact and explosive loadings. The latter group of fibers improves the strength and stiffness characteristics of concrete and, to a varying degree, its dynamic properties. Associated with the use of fibers is a host of technoeconomical questions that makes the choice of FRC over conventionally reinforced concrete difficult. There is definite potential for easier construction and weight reduction, wider joint spacings, added ductility, strength and toughness from the various types of fiber reinforcement. However, issues regarding fiber type and dosage, extent of performance improvement and economic cost still need to be clarified, primarily through additional field and laboratory testing.[1]

Current codes and standards restrict the engineering basis for fiber reinforcement to mostly non-structural, non-load bearing elements, notwithstanding slabs-on-grade and floor slabs.[2] These limitations reflect a certain lack of design and material-performance criteria. For instance, ASTM's 'Standard for Fiber-Reinforced Concrete and Shortcrete' classifies fiber types (e.g. synthetic fibers such as polypropylene, nylon, polyester, polyethylene, aramid, carbon and acrylic, glass fibers, and steel fibers) but does not define most individual fibers' mechanical and material properties. Practical design guidelines from ACI Committee 544[3] and from PCI cover some, but not all, FRC applications. Thus, FRC's structural value and performance characteristics cannot be fully exploited. The advantages of synthetic fibers are control and reduction of cracking plus increased elasticity and load-carrying potential. The fibers are chemically inert, relatively inexpensive (except for carbon and aramid fibers) and can be easily added in the mixing process. They do have certain shortcomings, however, such as occasional low fiber-to-matrix bonding, low modulus of elasticity (for polypropylene and polyethylene), and possibly slump loss in the mix. Finally, there are still open questions regarding performance testing.

Polypropylene fibers are probably the most popular synthetics because they are lightweight and very cost-competitive. They are produced as continuous cylindrical monofilaments that can be cut to specified length or in films and tapes and then formed into fine fibrils of rectangular cross-section. As with other synthetics, the design volume of polypropylene fibers is pivotal. For instance, research has confirmed that volumes of 2% or greater reduce drying-shrinkage and improve ultimate strength. Low volumes of 0.2%, however, offer little or no performance improvement. Also, design volumes for obtaining a significant postcracking load-carrying capability are greater when using discontinuous fibers, i.e. fibrillated tape or film and woven mesh configurations are more effective. Research work on the use of synthetic fibers (primarily polypropylene) as reinforcement in concrete includes testing programmes to determine basic load-deflection curves in compression and bending,[4,5] bonding characteristics,[6] resistance to impact loads, [7] torsional resistance,[8] durability and performance of sheeting elements[9–11] and determination of fracture characteristics[12] and of fatigue strength.[13] Also, there is work on determining the relative performance of various categories (steel, glass, synthetic) of fibers.[14,15] Other topics include testing for tensile behavior[16] as well as postcracking tensile strength[17] of FRC, use of fiber reinforcement in fly ash shotcrete,[18] corrosion of steel bars in FRC,[19] impact resistance of combined steel-synthetic FRC[20] and use of statistical concepts to derive effective moduli for FRC.[21,22]

The use of fibrillated polypropylene fibers in conrete slabs-on-grade to control shrinkage cracking and to increase impact resistance can be viewed as an alternative to welded wire fabric. The principle advantages that fibers offer are related to how they are incorporated in the structure. Welded wire fabric must be set manually on the subgrade and lifted into position while the concrete is placed, which increases both the construction time and labor costs of building the slab. Polypropylene fibers, however, are added to the concrete during mixing, thus eliminating reinforcement placing operations and their associated costs.[23] The inclusion of polypropylene fibers has also been shown[7,24–27] to increase the impact resistance of concrete. This is because polypropylene fibers' modulus of elasticity in tension is dependent on the rate of loading. Under static loading, the fibers' modulus is much smaller than that of the surrounding concrete. Therefore, the fibers do not contribute to the strength of the composite and, in fact, cause a small decrease in strength compared to an unreinforced specimen by taking up volume that would have otherwise been occupied by concrete. However, under dynamic loading, polypropylene fibers' modulus in tension becomes much larger, and is closer to that of the concrete. This increased stiffness, coupled with the fibers' rupture strength being greater than that of the concrete, causes the fracture strength of the composite to increase, with the magnitude of the enlargement being dependent on the rate of loading. Once the concrete matrix has begun to crack, the fibers act as crack arrestors, tying the partially broken sections together and allowing the slab to continue to carry the load.

To date, impact experiments have been performed using simply supported beams. The material's principal application, however, is on-grade slabs. Data are therefore needed to determine how the composite performs under impact loading when used in slabs-on-grade. The main thrust of this work is to furnish this information. To this effect, slabs with different fiber contents were tested for impact resistance when on-grade and, to determine the contribution of the subgrade, when simply supported. The results give an approximate relationship between fiber volume and impact strength for on-grade slabs that clearly shows an increase in the impact strength of the slab due to the fibers. Since polypropylene fibers increase the impact resistance of a slab-on-grade, an obvious application would be in machine pads. To avoid resonance phenomena, the design of such a pad would necessitate knowing the effect of the fibers on the natural frequency of the substructure. Therefore, prior to the impact test, the natural frequencies of the slab specimens were also measured. It was found that the presence of fibers has little effect on this dynamic property of the concrete slabs. These results were then reproduced using numerical techniques to confirm that standard mathematical models could be used to predict natural frequencies for design purposes. Several other experiments were also completed in conjunction with the impact and natural frequency tests. To ascertain the material strengths of the composite, standard compression and flexure tests were performed and, to determine the material properties of the subgrade, a series of geophone tests was conducted. Thus, with the impact resistance and natural frequencies known, engineers will be better able to judge the present uses of this material and to define other possible applications.

EXPERIMENTAL PROCEDURE

Model construction

The base concrete mix used in this experiment, a typical batch of which is shown in Table 1, had a nominal strength of 20 700 kPa without fibers. Three different concentrations of 19 mm nominal length fibrillated polypropylene fibers, as manufactured by Fibermesh, Inc., were used: unreinforced concrete (no fibers in the matrix); the fiber manufacturer's recommended volume (0.1% polypropylene fiber by volume); and an over reinforced mix (0.5% polypropylene fiber by volume). Each volume of fiber was prepared in a separate batch to ensure the concrete would not be overmixed during the construction of the models. Materials were drawn from the same sources for each batch so that any variance of the physical properties would be due to the volume of fibers contained in the specimens. For each batch, the concrete was first prepared, then the polypropylene fibers were added and 3–5 min of additional mixing time were allowed to achieve a good fiber dispersion.

Table 1. Typical concrete mix

Component	*Weight (kg)*
Water	34.1
Cement	58.6
Coarse aggregate	110
Fine aggregate	146

Note: mix volume is approximately 1.49 m^3.

To help isolate the contribution of the fibers from that of the subgrade, two slabs were constructed for each of the three fiber volumes. The first group was tested on the ground where formed (the on-grade slabs), while the second group was tested on a circular manhole frame with only its edge supported (the elevated slabs). Since the spring weather was mild, all six slabs were constructed and tested outdoors on a smooth clay ground surface, exposed to the environment. Molds were composed of a 20 mm section of square plywood base with a 0.94 m-diameter circular segment removed with wood shims placed around the hole's perimeter and a 76 mm-high section of oiled sheet metal inserted to form the slab's boundary. Plastic sheeting was stapled to the bottom of the elevated slab's formwork so they could later be easily separated from the subgrade. Concrete was shoveled into the center of each mold and pushed outward to form the slab, and a float finish was applied. To help minimize water loss, the models were covered with plastic sheeting for 3 days and watered twice a day for a week. The models were allowed to cure for 35 days before being tested. The weather for this period was mild, with predominantly sunny days and temperatures ranging from 10 to 20°C. All specimens had a width-to-depth ratio of 12:1.

Three cylinder (150 mm in diameter by 300 mm high) and three beam (100 mm × 100 mm × 360 mm) specimens were also prepared from each batch and cured in a moist room for 28 days. Concrete cylinders were tested using the procedure specified in ASTM C39-86 'Compressive Strength of Cylindrical Concrete', using a standard testing machine. Beam specimens were tested as specified in ASTM C78-86 'Flexural Strength of Concrete (Using Simple Beam With Third Point Loading)' using the optional steel rod to transfer the load from the head of the testing machine to the steel bearing plate. The 28-day compressive and flexural strengths of the cylinder and beam specimens, respectively, are given in Table 2.

The results, for both compressive and flexural strength, show an inverse relationship between fiber content and strength, verifying results obtained by Nagabhushanam et al.[27] and Hughes and Fattuhi.[4] The decrease in strength with increasing fiber content can be attributed to the tests being quasi-static and to the tension modulus of the fiber being rate-dependent. In the models containing fibers, the lower modulus

Table 2. 28-Day mix strength

(a) Compressive strength

Cylinder	*Fiber volume (%)*	*Sample f'_c (kPa)*	*Average f'_c (kPa)*
A-1	0.0	28 550	
A-2	0.0	24 900	27 800
A-3	0.0	26 880	
B-1	0.1	22 930	
B-2	0.1	19 280	22 830
B-3	0.1	26 245	
C-1	0.5	17 070	
C-2	0.5	20 520	19 030
C-3	0.5	19 520	

(b) Flexural strength

Beam	*Fiber volume (%)*	*Sample f'_c (kPa)*	*Average f'_c (kPa)*
A-1	0.0	3410	
A-2	0.0	3550	3280
A-3	0.0	2830	
B-1	0.1	2970	
B-2	0.1	2830	3030
B-3	0.1	3340	
C-1	0.5	3070	
C-2	0.5	2660	2720
C-3	0.5	2480	

fibers takes up a volume that would have been filled by the higher strength concrete, thus causing the reductions in strength.

Impact test

The drop mechanism, shown in Fig. 1, weighted 30 kg. The drop height was found by determining the static force required to cause the elevated, unreinforced slab to fail. This, using thin plate theory and the rupture stress of the concrete, was found to be 10.68 kN.[28] Since the results of the experiment were used to compare the impact resistance of the slabs, a minimum of two blows to cause failure was required for all models. Therefore, the actual force of impact had to be less than the static force predicted by thin plate theory to cause failure. In order to ascertain the amount of force generated by the drop mechanism, the weight was released from different elevation and allowed to fall on a concrete specimen, made from the original batches, which rested on a pressure transducer. The results indicate that the impact force produced was independent of the fiber content of the test specimen. A height of 0.76 m was then chosen for the experiment because it produced a measured impact force of 8.90 kN. Each specimen was tested by centering the drop mechanism on the middle of the slab and

Fig. 1. Drop mechanism.

counting the number of blows required to cause failure, which was defined as any crack pattern that, if present in the elevated slab, would cause collapse. The number of blows to first cracking and the number to cause failure are presented in Table 3 and in Fig. 2. It is clearly illustrated that the addition of fibrillated polypropylene fibers to the concrete mix significantly improves the first cracking strength of the on-grade slabs as well as the fracture strength of both elevated and on-grade slabs.

Natural frequency test

The center, quarter, half, and three-quarters points were marked on each slab along the diameter, and an accelerometer was affixed to the center point using soft candle wax. The marked locations were then tapped in turn with a lead-tipped hammer, and the resulting complex frequency responses were recorded.[29] The theoretical analysis of the natural frequency of the on-grade slabs required knowledge of the material properties of the subgrade. To this purpose, boring logs of the site were consulted, and a series of geophone tests was conducted.[28] Table 4 gives the fundamental frequency measured at the center, quarter, and half points for each slab specimen.

Table 3. Impact resistance and relative fracture strength

Boundary condition	*Fiber volume (%)*	*Blows to 1st crack*	*Blows to failure*	*Relative strength*
Elevated	0.0	1	2	1.0
	0.1	1	7	3.5
	0.5	3	12	6.0
On-grade	0.0	1	6	3.0
	0.1	3	6	3.0
	0.5	6	20+	10.0+

Discussion of experimental results

Impact tests

The experimental results presented in Table 3 and Fig. 2 indicate, whether elevated or on-grade, that the presence of fibrillated polypropylene fibers has a distinct, positive effect on the impact resistance of a slab. The sole exception to this was the 0.1% slab-on-grade, which failed after the same number of blows as its unreinforced counterpart. Since this specimen also failed sooner than the 0.1% elevated slab, which, because of its support conditions, should have been weaker, the on-grade model was probably flawed during construction.

Improvement was especially pronounced for the slab-on-grade containing the maximum fiber content, 0.5%. Testing was halted on this slab after 20 blows because no further damage had occurred from when the specimen had initially

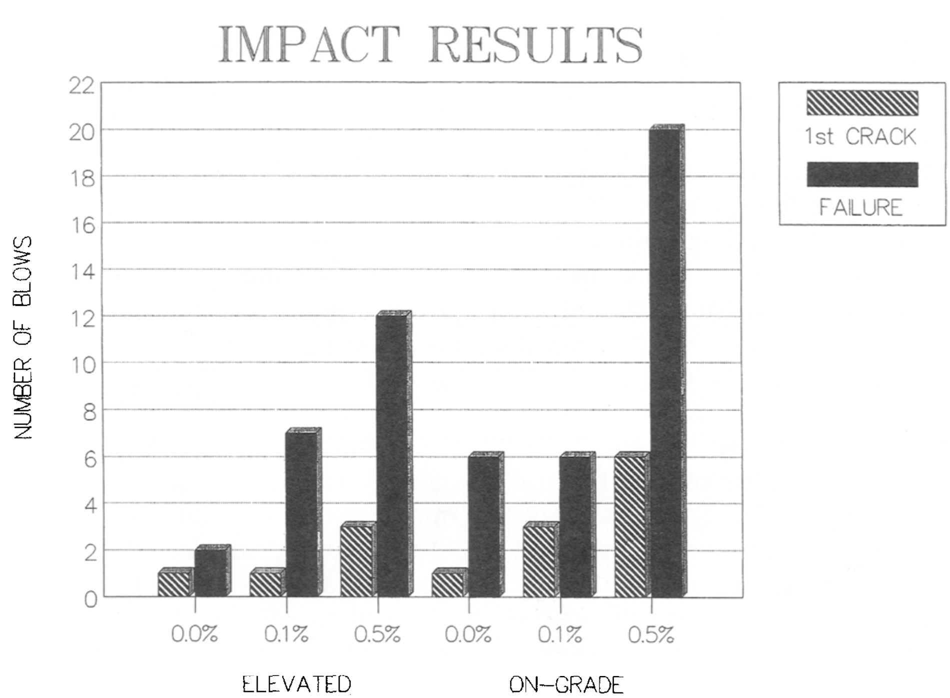


Fig. 2. Impact resistance of slabs.

Table 4. Measured first natural frequency (Hz)

Boundary condition	*Fiber volume (%)*	*Center point*	*Quarter point*	*Half point*	*Average*
Elevated	0.0	28	28	28	28
	0.1	32	32	32	32
	0.5	28	28	28	28
On-grade	0.0	140	140	120	133
	0.1	150	120	120	130
	0.5	130	110	110	127

cracked. To clarify what failure pattern was forming, the drop height was raised from 0.76 m to 2.10 m, and testing was resumed. Three additional blows were required from the new elevation to complete the failure mechanism. Using the fracture strength of the elevated, unreinforced slab as a base, the relative strengths of each specimen was calculated and is also presented in Table 3. It is worth noting that as the fiber content is increased, the relative strength improves markedly, particularly so for the 0.5% fiber case.

Fracture patterns were also affected by fiber volume. All slabs, regardless of their fiber content and their support condition, ultimately failed in bending, the pattern for which is characterized by a set of three or more radial cracks extending the depth and radius of the slab, as shown in Fig. 3. The unreinforced specimens exhibited sudden and catastrophic bending failure. The presence of fibrillated polypropylene fibers in the slabs resulted in a more gradual failure. Thus, the fibers changed the nature of the failure mode to a less brittle one. This change was influenced by both fiber volume and support conditions of the specimens. Also, the elevated fiber reinforced slabs displayed a partial shear punching mechanism, whose pattern is a semicircular crack around the center of the slab extending the slab's depth.

The more complicated failure patterns exhibited by the elevated, fiber reinforced slabs are due to the increased contribution, under dynamic loading, to the composite's flexural strength by the polypropylene fibers. This increase allows a shear mechanism to start, but the pattern is not completed because, after the concrete has cracked, the fibers along this plane are put into tension, increasing the shear strength and re-establishing the bending mechanism as the critical pattern. Ultimately, the elevated, reinforced models failed when the polypropylene fibers were pulled out of the concrete. That the reinforced slabs on grade do not exhibit shear punching failures can be attributed to the continuous support supplied by the subgrade, which reduces the shear force carried by the slab so that the maximum shear stress of the composite is never exceeded. This behavior conforms with the Eurocode 2[30] provisions for foundation slabs, which permit the reduction of the applied shear so as to allow for soil reaction within the critical perimeter. As expected, the slabs with the subgrade boundary condition performed better than their elevated counterparts. This was due to the ground behaving like a continuous elastic support which reduced the bending moment in the slabs, and thus reduced the corresponding tensile stress.

Natural frequency tests

The results in Table 4 show that polypropylene fiber content did not have a noticeable affect on the first natural frequence. This can be explained by recourse to a simple, single degree of freedom (SDOF) model of the slab. In such a model, the two factors that control the natural frequency are the mass of the slab and its static stiffness. The inclusion of the light-weight fibers in the small volumes used in this experiment do not produce a significant change in the mass and, since the natural frequency test is quasi-static, the fibers do not exhibit a higher, rate dependent modulus, and therefore the stiffness would not be appreciably altered. As would be expected, the on-grade slabs had a much higher frequency than the elevated slabs because of the additional virtual mass supplied by the subgrade.

Numerical simulation

Determining the natural frequency for the slab-on-grade is a difficult problem because the boundary of the participating soil mass is ill-defined, as are the *in-situ* material properties. To simplify the problem, Richart *et al.*[31] suggested replacing the subgrade with a virtual mass added to that of the slab, a massless spring, and a massless dashpot. For this model, the virtual mass would have the same density as the soil, cover the same area as the plate, and have a thickness $t = 0.27\sqrt{A}$, where A is the contact area of the slab and subgrade. The stiffness and damping coefficients then are

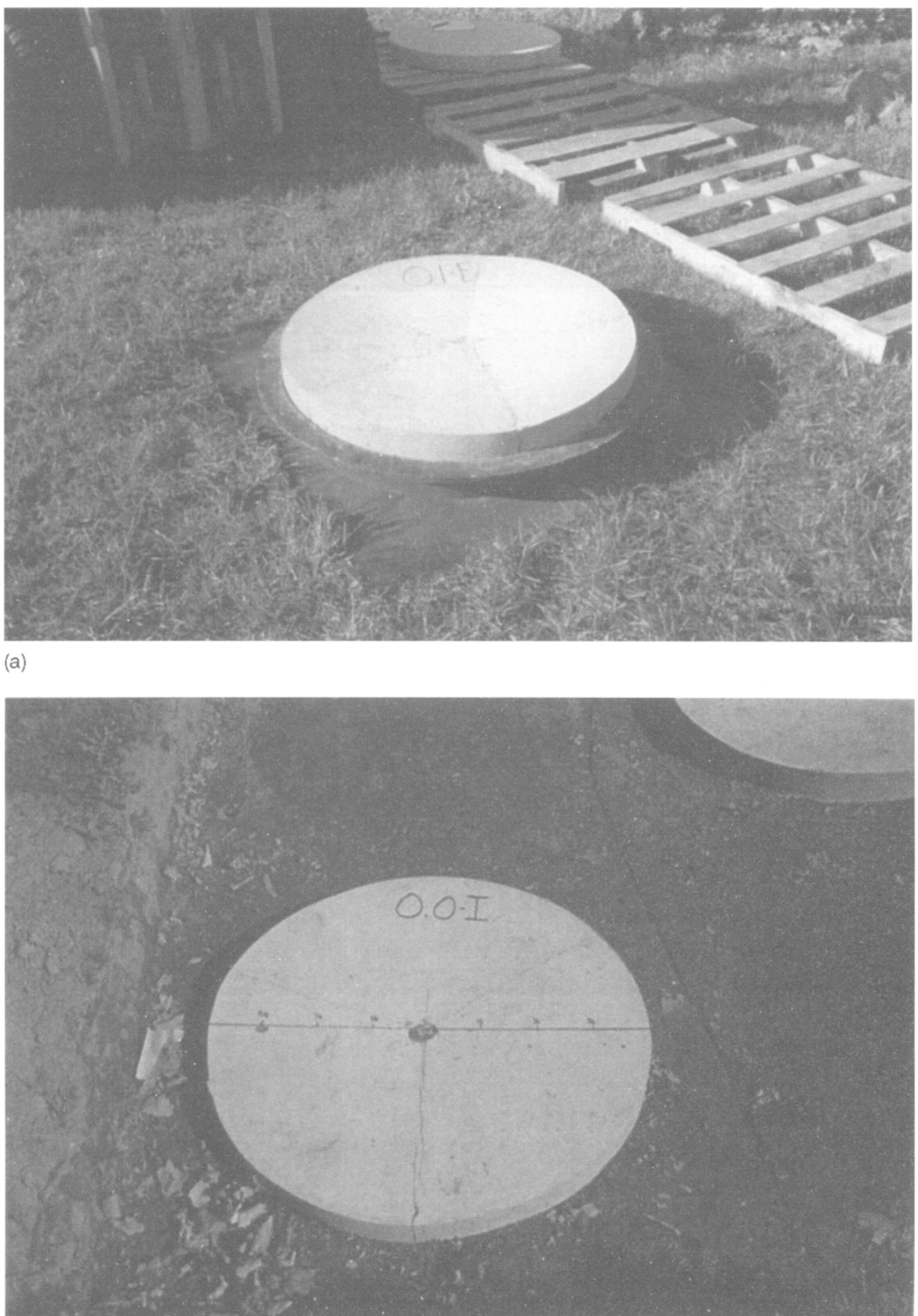
$$K = 4Gr/(1-\mu) \quad (1)$$

$$C = 0.85Kr/V_p \quad (2)$$

where K is the spring constant, C is the damping coefficient, G is the soil's shear modulus, r is the radius of the slab, μ is the soil's Poisson ratio, and V_p is the velocity of pressure waves in the soil. Assuming that the slab is rigid compared to the subgrade, the model stiffness is approximately equal to that of the virtual volume of soil. Then, using the SDOF model, the first natural frequency of the slab-on-grade is

$$f = (1/2\pi)\cdot\sqrt{[K/(M_{soil}+M_{slab})]}. \quad (3)$$

For this problem, the radius of the slab is 0.47 m. Therefore, the contact area is 0.69 m^2, the thickness of the virtual volume of soil is 0.22 m, and the virtual volume is 0.16 m^3. The virtual mass of soil, using an estimate for the denstiy of clay of 2000 kg/m^3 based on the bor-



(a)

(b)

Fig. 3. Typical failure patterns of (a) elevated slab and (b) slab-on-grade.

ing logs, is then 320.0 kg. The mass of the slab, using a unit weight for concrete of 2400 kg/m^3, is 126.0 kg.

To determine the equivalent spring constant, the shear modulus of the soil is needed. Utilizing elastic theory, G can be related to μ and V_p by the relationship

$$G = 0.5V_p^2\rho\cdot[(1-2\mu)/(1-\mu)], \tag{4}$$

where ρ is density of the soil equal to 2000 kg/m^3. The average pressure wave speed, determined from the geophone test,[28] was found to be 470 m/s. Inserting these values into eqn 4 yields

$$G = 220.9\ 10^6\cdot[(1-2\mu)/(1-\mu)] \tag{5}$$

in Pa. With the shear modulus known, the stiffness can be calculated from eqn (1) and is

$$K = 415.2\ 10^6\cdot[(1-2\mu)/(1-\mu)^2] \tag{6}$$

in N-m. Thus, the natural frequency is

$$f = 156\sqrt{(1-2\mu)}/(1-\mu). \tag{7}$$

Poisson's ratio is difficult to determine. For undisturbed clay, however, the range is rather small. Realizing this, typical values of μ for clay were used to calculate the natural frequency of the on-grade system, and the results are tabulated in Table 5. An average of natural frequencies from the experimental results yields a frequency of 128 Hz. This agrees very well with the range of frequencies shown in Table 5. Therefore, the approximate method is a suitable technique for use in design.

CONCLUSIONS

As demonstrated in this experimental study, the inclusion of three-quarters of an inch long, fibrillated polypropylene fibers significantly improves the impact resistance of concrete slabs without affecting the natural frequency. However, the static compression and flexural strength decrease with increasing fiber content. With this information known, some of the possible applications of the composite are in machine pads, in warehouse and loading dock slabs, in sidewalks, and in roads. Several areas of interest remain to be explored. These include: utilizing a different material, such as crushed stone or sand, as the sub-base; varying the fiber length; trying different mix designs to maximize the fibers' contribution to strength; comparing the impact resistance of concrete slabs reinforced with polypropylene fibers to concrete reinforced with welded wire fabric; and determining how weathering affects the impact resistance.

Table 5. Numerically determined natural frequencies for slab on grade

Poisson's ratio	*Natural frequency (Hz)*
0.30	140.61
0.31	139.03
0.32	137.31
0.33	135.44
0.34	133.63
0.35	131.38
0.36	128.91
0.37	126.19
0.38	123.19
0.39	119.88

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