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Carbon fiber-reinforced concrete for traffic monitoring and weighing in motion

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Abstract

The use of carbon fiber (5 mm long, 0.5% or 1.0% by weight of cement) reinforced concrete for traffic monitoring and weighing in motion was demonstrated in the laboratory for stresses up to 1 MPa and speeds up to 55 mph. The DC electrical resistance decreased with increasing stress and was independent of speed. Resistance was measured with the four-probe method, using continuous carbon fibers together with silver paint as electrical contacts. The resistance change was reversible upon unloading.

Keywords: Electrical properties; Concrete; Fiber reinforcement; Strain effect; Weighing

Traffic monitoring, an essential part of traffic control and management, involves real-time monitoring and requires strain sensors, which may be optical, electrical, magnetic, or acoustic. The sensors are conventionally attached to or embedded in the highway for which traffic monitoring is desired. The sensors suffer from (1) their sensing ability being limited to their immediate vicinities, (2) they are not sufficiently durable, and (3) they are too expensive for widespread use. A relatively new technology involves the use of concrete itself as the sensor, so that no embedded or attached sensor is needed [1–8]. Because the structural material is also a sensor, the whole structure is sensed and the sensor (just concrete) is durable and inexpensive. Hence, all three problems for conventional sensors are removed by the use of this self-monitoring concrete.

The weighing of vehicles such as trucks is needed to avoid damage to highways due to overweight vehicles. It is currently conducted in weighing stations off the highway while the vehicle is stationary. The monitoring of the weight of vehicles can be more convenient and effective if the weighing is done on the highway while the vehicle is moving normally. In this way, traffic is not affected and time is saved. If the whole highway is capable of weighing, the monitoring is continuous and hence is more thorough than the current method. This paper demonstrates the effectiveness of self-monitoring concrete for weighing vehicles in motion.

The self-monitoring concrete is concrete containing a small amount (typically 0.2–0.5 vol%) of short carbon fibers. The sensing ability stems from the fact that the fibers are much more electrically conducting than the concrete mix. The fibers bridging microcracks in the concrete undergo slight (<1 μm) pullout as the concrete is deformed, thereby increasing the volume electrical resistivity of the concrete. This effect is reversible upon unloading, so that the reversible resistivity increase provides an indication of the reversible strain. The strain sensitivity (gage factor, i.e., fractional change in electrical resistance per unit strain) is as high as 700.

Self-monitoring concrete can be used for retrofits or new installations. Due to the low drying shrinkage of this concrete [9], it bonds well to old concrete [10]. Due to the low cost of this concrete compared to concrete with embedded or attached sensors per unit sensing volume, the use of self-monitoring concrete is economical. An added attraction is that self-monitoring concrete exhibits high flexural strength, high flexural toughness, and low drying shrinkage [9,11]. Therefore, the use of self-monitoring concrete provides not only smart highways, but also structurally superior highways.

The strain sensing ability of self-monitoring concrete under dynamic loading (tensile, compressive, and flexural) at different strain rates and stress amplitudes has been reported [5,6]. This paper provides a laboratory demonstration of the

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use of self-monitoring concrete for traffic monitoring and weighing in motion. For this purpose, a vertical wheel (a car tire) is allowed to rotate against the cylindrical surface of two horizontal concrete rollers (corresponding to the highway), as illustrated in Fig. 1. The speed of wheel rotation (which corresponds to the speed of the car) and the force applied (via bolt and nuts, Fig. 1c) between the wheel and the concrete rollers (the force corresponding to the weight of the car) are systematically varied. On the surface of one of the rollers (made of self-monitoring concrete) is a one-dimensional array (in the direction of the wheel travel, Fig. 1b) of four electrical contacts for measurement of the electrical resistance of the concrete near its surface as the wheel rolls on it. The normal compressive stress from the wheel to the roller results in a compressive stress tangential to the surface of the roller due to the flexural stress. The compressive stress results in a reversible compressive strain, which in turn causes a reversible resistance decrease. Resistance measurement allows real-time monitoring of the stress imposed on the roller by the wheel.

1. Experimental methods

The carbon fibers were isotropic pitch based, unsized, and ~5 mm long, as obtained from Ashland Petroleum Co. (Ashland, KY). The fiber properties are shown in Table 1 of reference [1]. Ozone treated fibers [1,2] were used. The ozone treatment involved exposure of the fibers to O_3 gas (0.6 vol%, in O_2) at 160°C for 5 min. Before O_3 exposure, the fibers had been dried at 110°C in air for 1 h. The dispersion of the carbon fibers requires additives, i.e., methylcellulose and silica fume. Carbon fibers in amounts of 0.15 and 0.30 vol% (corresponding to 0.5% and 1.0% by weight of cement) were used.

Portland cement (type I) from Lafarge Corp. (Southfield, MI) was used. The sand was natural sand (all passing #4 US sieve, 99.9% SiO_2), with particle size analysis shown in Fig. 1 of reference [8]. The sand-to-cement ratio was 1.5. The water-to-cement ratio was 0.45. The water-reducing agent powder was TAMOL SN (Rohm and Haas), which contained 93–96% sodium salt of a condensed naphthalene sulfonic acid; it was used in the amount of 2% by weight of cement. The silica fume (Elkem Materials, EMS 965) was used in the amount of 15% by weight of cement. Methylcellulose (Dow Chemical, Methocel A15-LV) in the amount of 0.4% of the cement weight was used. A defoamer (Colloids 1010) was added in the amount of 0.13 vol%. The coarse aggregate (all passing 1-inch sieve) was such that the cement, sand, and coarse aggregate were in the weight ratio 1:1.5:2.5.

Two fifths of the total amount of water was heated to 80°C. Then methylcellulose was added to the water and stirred. Carbon fibers were added and mixed in a Hobart mixer for ~5 min. The defoamer was added. Cement, sand, coarse aggregate, and silica fume were separately mixed for 5 min in a concrete mixer. The fiber mix was added to the concrete mixer and mixed for 5 min. The remaining three fifths of water was added and mixed for ~5 min. The water-reducing agent was added and mixed for 10 min. The mix was poured into cylindrical molds of diameter 12.5 inch (318 mm) and length 7.5 inch (191 mm). Oil was applied to the inner surface of the mold before the concrete mix was poured into the mold. After pouring, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The cylinders were demolded after 24 h and cured in air with a relative humidity of 100% for 28 days.

Four electrical contact strips were laid on the surface of the right concrete roller (Fig. 1b). Each strip is a tow of continuous carbon fibers (pitch-based, Thornel P-25, 10-μm fiber diameter, 2000 fibers per tow, 3-mm tow width, no sizing, no twist, from Amoco Performance Products, Inc., Ridgefield, CT) of length 7.5 inch (191 mm), together with silver paint. The four strips are equally spaced, such that the inner edges of adjacent strips are 20 mm apart. The two outer strips serve as current contacts; the two inner strips serve as voltage contacts. This is in accordance with the four-probe method of resistance measurement. DC electrical measurement was conducted by using a Keithley 2001 multimeter, which was connected via four carbon brushes (Fig. 1e) and four copper slip rings (Fig. 1d) to four copper wires embedded at the other end into the four fiber strips for a length of 10 mm for each wire (Fig. 1b). The strips with the embedded wire ends were covered by plastic adhesive tape, which served to protect the electrical contacts. The four wires were collected at four copper slip rings at the axis (1030 steel shaft) of the concrete roller to allow electrical measurement to be made while the roller was rotating. Electrical contacts in the form of continuous carbon fibers were more reliable than those in the form of copper foils. Electrical contacts degraded as the speed increased if silver paint was not used.

An ordinary passenger car wheel (with tire) of diameter 23 inch (584 mm) was placed on the two concrete rollers, such that the vertical distance between the axis of the car wheel and the axis of either concrete roller was 15.75 inch (400 mm), as shown in Fig. 1a. The horizontal distance between the axes of the two concrete rollers was 16 inch (406 mm). A motor was used to turn the left concrete roller anticlockwise. This caused the car wheel to turn clockwise while the right concrete roller turned anticlockwise. A photodetector (Fig. 1b) was used to trigger the data acquisition system so that electrical resistance measurement was conducted during the rotation of the right concrete roller at the time when the car wheel was in contact with the electrical contact strips. Thus, each cycle of rotation yielded one data point. At least 200 data points (after the initial ~50 cycles, during which stabilization occurred) were taken for each combination of speed and stress. For each stress level, measurement was made before and after unloading to investigate the reversibility of the electrical resistance change. The load, as applied by bolt and nuts, and sensed by a load sensor (LCW-1K, Omega Engineering, 1000-lb capacity, Fig.

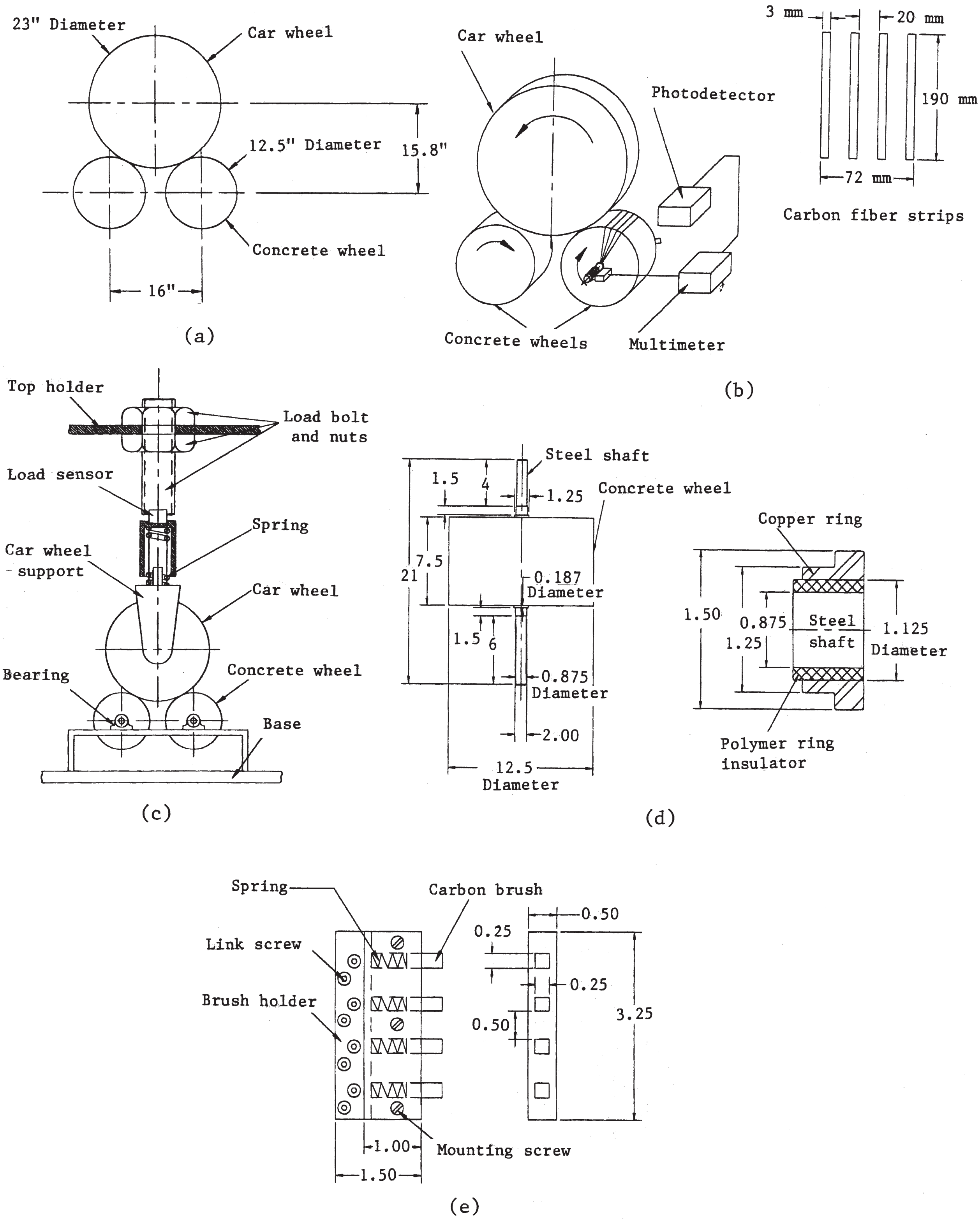

Fig. 1. Testing set-up. Dimensions are in inches unless stated otherwise. *(a)* Two-dimensional view. *(b)* Three-dimensional view and electrical contact geometry. *(c)* Loading mechanism. *(d)* Steel shaft and copper slip ring. *(e)* Carbon brush assembly.

1c), was such that 500 lb of applied load corresponded to a stress of 1.03 MPa on the stressed part of the concrete roller.

The main difference between the laboratory demonstration and field demonstration is that the concrete roller in the former gets warm due to the cyclic rubbing by the car wheel, whereas concrete in the latter does not get warm due to the rubbing at a point in the concrete highway occurring once by a vehicle. To eliminate this difference, the concrete roller in this work was kept cool by a fan.

2. Results and discussion

Fig. 2 shows the effect of normal stress on electrical resistance during loading in the static condition (speed = 0) for self-monitoring concretes with carbon fibers in amounts of 0.5% and 1.0% by weight of cement. The resistance decreases with increasing stress and with increasing fiber content. The resistance change is totally reversible at all stress levels, as shown by the data obtained after unloading at each stress level. Fig. 3 shows the effect of speed for self-monitoring concretes with carbon fibers in amounts of 0.5% and 1.0% by weight of cement. At each stress level, the resistance is independent of speed. The resistance change is totally reversible at all stress levels and at all speeds.

Figs. 2 and 3 indicate that self-monitoring concrete can monitor traffic and weigh vehicles in motion by sensing in real time the normal stress due to vehicles up to at least 1 MPa at vehicle speeds up to at least 55 mph. The output is the electrical resistance, which decreases reversibly with increasing stress and is independent of speed. The concrete contains short carbon fibers in amounts of 0.5% or 1.0% by weight of cement. The higher fiber content yields lower resistance and less noise, but it involves higher cost.

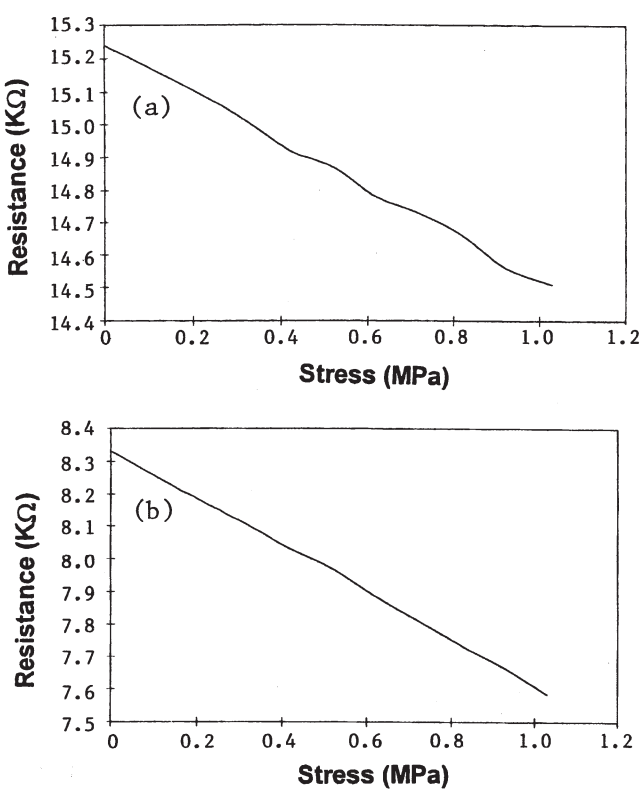

Fig. 2. Effect of stress on resistance at zero speed for self-monitoring concrete with carbon fibers in amounts of *(a)* 0.5% and *(b)* 1.0% by weight of cement.

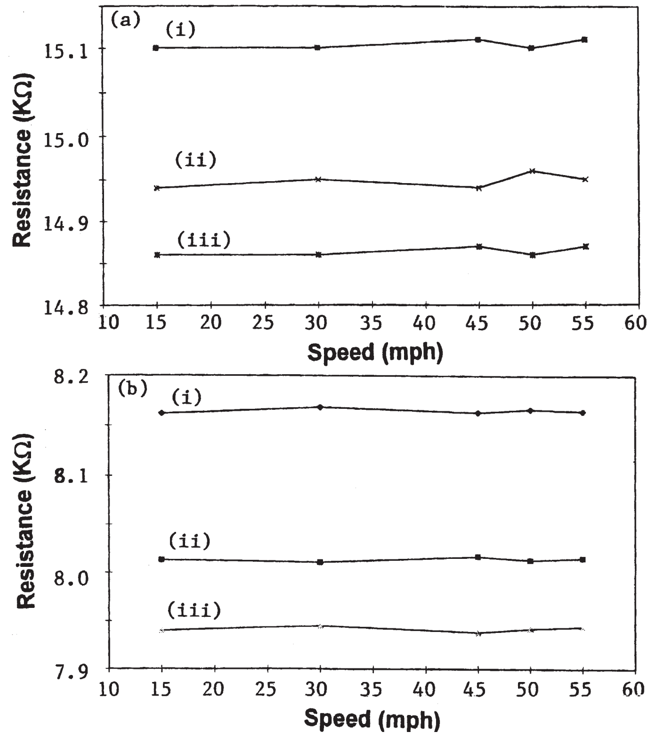

Fig. 3. Effect of speed on resistance at a constant stress for self-monitoring concrete with carbon fibers in amounts of *(a)* 0.5% and *(b)* 1.0% by weight of cement. (i) 0.21 MPa; (ii) 0.42 MPa; (iii) 0.52 MPa.

3. Conclusion

Self-monitoring concrete containing short carbon fibers (0.5% or 1.0% by weight of cement) is effective for traffic monitoring and weighing in motion. The resistance decreases reversibly with increasing stress up to 1 MPa and is independent of speed up to 55 mph.

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