Feasibility of Lightweight Cellular Concrete for Vehicle Crash Cushions

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Three vehicle crash tests of lightweight cellular concrete crash cushions are reported, along with proposed procedures for cast-in-place and precast construction of these devices. This crash cushion, composed of vermiculite concrete, lightweight welded wire fabric, and cylindrical cardboard forms, is designed to protect motorists from collisions with rigid obstacles located along the roadway. The crash cushion has proved crash-worthy under head-on test conditions.

•CELLULAR concrete structures have been proposed as vehicle deceleration devices in a recent feasibility study by Cornell Aeronautical Laboratories (1). Three vehicle crash tests have been conducted on a lightweight cellular concrete crash cushion (designed by personnel of the Texas Transportation Institute) with very favorable results. The crash cushion is composed of vermiculite concrete with hollow cardboard tubes (23 in. in diameter) spaced throughout to provide the necessary voids. Lightweight welded wire fabric is used as reinforcement for the vermiculite. The first concrete crash cushion constructed is shown in Figures 1 and 2.

The concrete used for the crash cushions in this study was composed of cement, water, and a commercial grade of vermiculite. This vermiculite aggregate was very uniform in gradation. Vermiculite is a kiln-expanded mica. Since mica is a rock composed of many thin layers, it is subject to high expansion, leaving spaces between these layers. The average size particle is approximately a ⅛-in. cube. On close examination, a single cubical particle looks like a tiny accordian. These small cubes can be compressed to a flat particle by slight pressure. The extreme light weight (per bulk volume) of this aggregate in combination with a high degree of air entrainment produces a very lightweight, low-strength concrete.

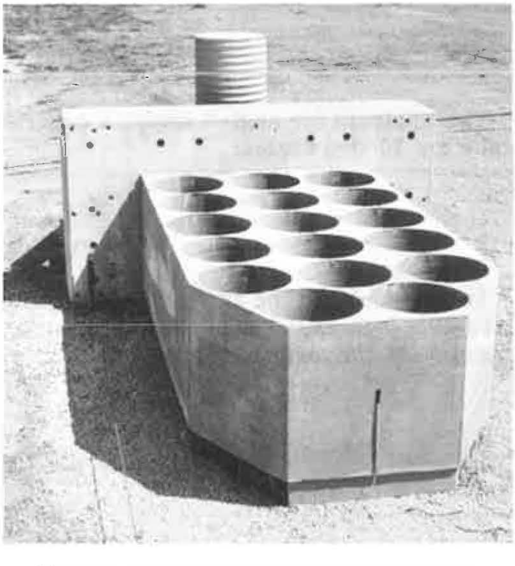

Figure 1. Prototype of concrete crash cushion.

MATERIALS AND CONSTRUCTION

A 1:7 mixture of vermiculite concrete was used in all three crash cushions. Coarse vermiculite aggregate and type III cement were used in the cushions for

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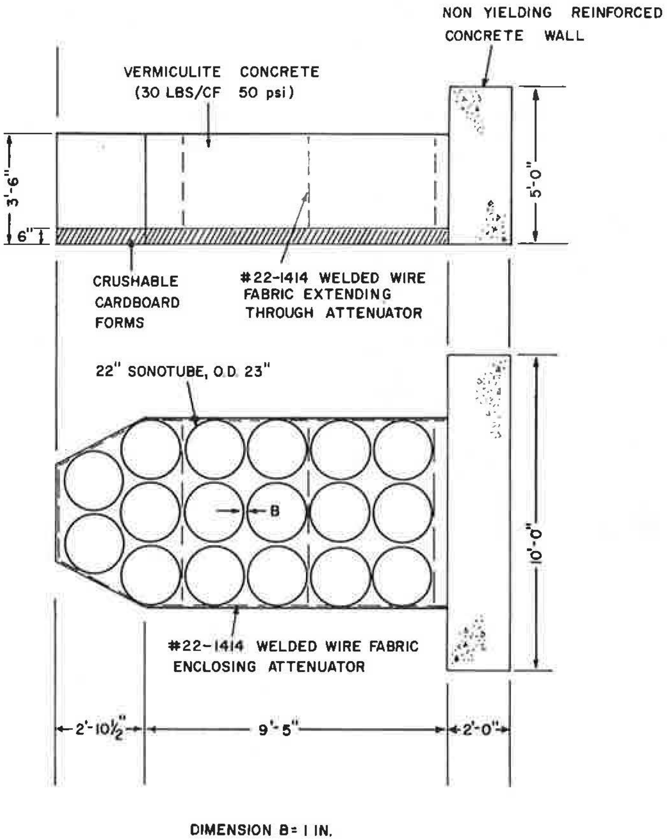


Figure 2. Concrete crash cushion, Test A.

Tests A and B. Welded wire fabric (24-1414) reinforcement was placed longitudinally in each side wall and transversely between each row of sonotubes in the Test A cushion. In the Test B cushion, a layer of this wire fabric was also placed in the top and bottom surfaces. Mixture proportions and properties of the concrete are given in Table 1. Folding cardboard carton forms were used as the bottom form with reinforced ¾-in. plywood sheets used for the side forms. In Tests A and B, the cardboard carton forms

TABLE 1

MIXTURE PROPORTIONS AND PROPERTIES OF VERMICULITE CONCRETE

Test	Aggregate	Cement	Water	Wet Unit Weight	Dry Unit Weight	Compressive Strength
A	121.3 lb/cu yd 20.2 cu ft/cu yd	272 lb/cu yd 2.9 sacks/cu yd	607 lb/cu yd 72.9 gal/cu yd 25.1 gal/sack	37 lb/cu ft	32 lb/cu ft at 12 days	50 psi at 12 days
B	140 lb/cu yd 23.4 cu ft/cu yd	312 lb/cu yd 3.34 sacks/cu yd	629 lb/cu yd 75.5 gal/cu yd 22.6 gal/sack	40 lb/cu ft	32 lb/cu ft at 18 days	71 psi at 13 days
C	150 lb/cu yd 23.0 cu ft/cu yd	305 lb/cu yd 3.24 sacks/cu yd	645 lb/cu yd 77.4 gal/cu yd 23.9 gal/sack	41 lb/cu ft average	21 lb/cu ft at 30 days	57 psi at 30 days

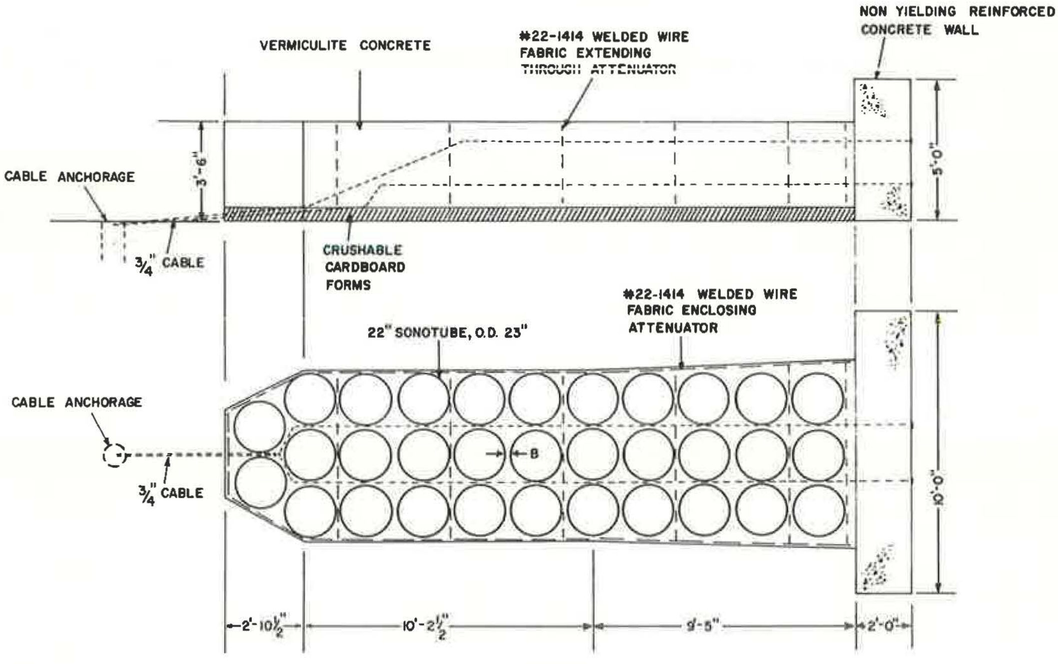
Figure 3. Precast vermiculite module.

remained in place and supported the cushion 6 in. above ground level when installed at the test site. The sonotube spacing was maintained with small wooden blocks.

The cushion for Test A was cast as a single unit, then transported to the test site and installed. The Test B cushion was cast in place at the test site. Precast modules were used in constructing the cushion for Test C. One of the three-tube modules is shown in Figure 3. The welded wire fabric was placed in all four outside walls of the forms. Using a new fast-setting cement developed by the Portland Cement Association, the forms were removed in less than 2 hours after casting. This cement was furnished by the Lone Star Cement Corporation and is still in the experimental stage.

TEST PROGRAM

Three full-scale vehicle crash tests of the lightweight cellular concrete crash cushion have been conducted. Electronic accelerometers and an Impact-O-Graph were used in each test to record decelerations. High-speed cameras (500 frames per second) recorded the crash, and analysis of the film gives vehicle displacement and velocity with respect to time. Rough estimates of



DIMENSION B = 2 IN.

Figure 4. Concrete crash cushion, Test B.

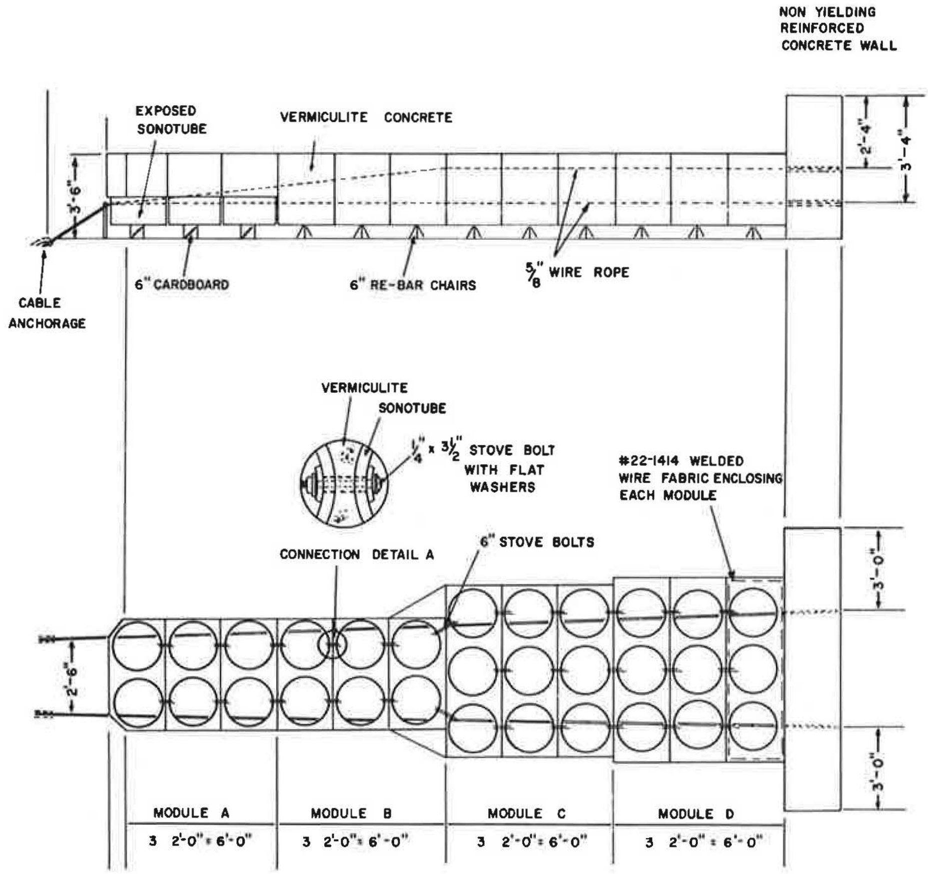


Figure 5. Concrete crash cushion, Test C.

deceleration over distances of several feet can also be achieved by analysis of the photographs of the vehicle and crash cushion and sequential photographs of the test in progress are included.

Crash Tests

In Test A, only half of the proposed full-sized crash cushion was fabricated. The first 12 ft of the cushion, shown in Figure 1, was subjected to a low-speed test (41 mph) by a 3,650-lb vehicle. In Test B, a full-sized crash cushion (24 ft in length) was cast in place (Fig. 4). In this test, a 3,200-lb vehicle impacted the cushion at a velocity of 59 mph. In Test C, the precast modular construction technique was used and the barrier was put together in the field using three-tube and two-tube modules. The design of this cushion is shown in Figure 5. A 4,560-lb vehicle traveling 64 mph impacted this crash cushion head on. For comparison purposes, the test of a 3,270-lb vehicle

Figure 6. Crash Test D (immovable wall).

TABLE 2

SUMMARY OF TEST DATA

Factor	Test			
	A	B	C	D (Rigid Wall)
Vehicle year, make, and model	1956 Pontiac 4-door	1963 Dodge 4-door	1958 Oldsmobile 2-door	1963 Plymouth 4-door
Vehicle weight (W), lb	3,650	3,200	4,560	3,270
Vehicle velocity (V), fps	60.3	86.2	93.3	78.3
mph	41.1	58.8	63.6	53.3
Stopping distance (D), ft	9.0	11.2	21.4	3.82
Maximum deceleration (longitudinal), g	10.5[a]	20.5[a]	10.4[a]	35[a]
Average deceleration (longitudinal), g	5.1[a] 6.3[b]	6.6[a] 10.3[b]	6.5[a] 6.3[b]	25[b]
Attenuation index[c]				
$AI_{(max)} = \frac{G\text{ (maximum test)}}{G\text{ (maximum rigid)}}$	0.29	0.39	0.18	0.73
$AI_{(avg)} = \frac{G\text{ (average test)}}{G\text{ (average rigid)}}$	0.27	0.31	0.17	0.82

[a] Electronic accelerometer; data on Test B not reliable due to zero shift.

[b] Calculated from stopping distance.

[c] G (maximum rigid) = 0.9V, G (average rigid) = 0.574V, V in mph (2).

traveling 53 mph and impacting a rigid wall is included. This test is designated D and is shown in Figure 6.

These four head-on tests are summarized in Table 2. In Test A (Fig. 7), the 1956 Pontiac was stopped in 9 ft with an average barrier force of 23,000 lb. The average deceleration was 6.3 g, which is considered an acceptable level. Test B illustrated the

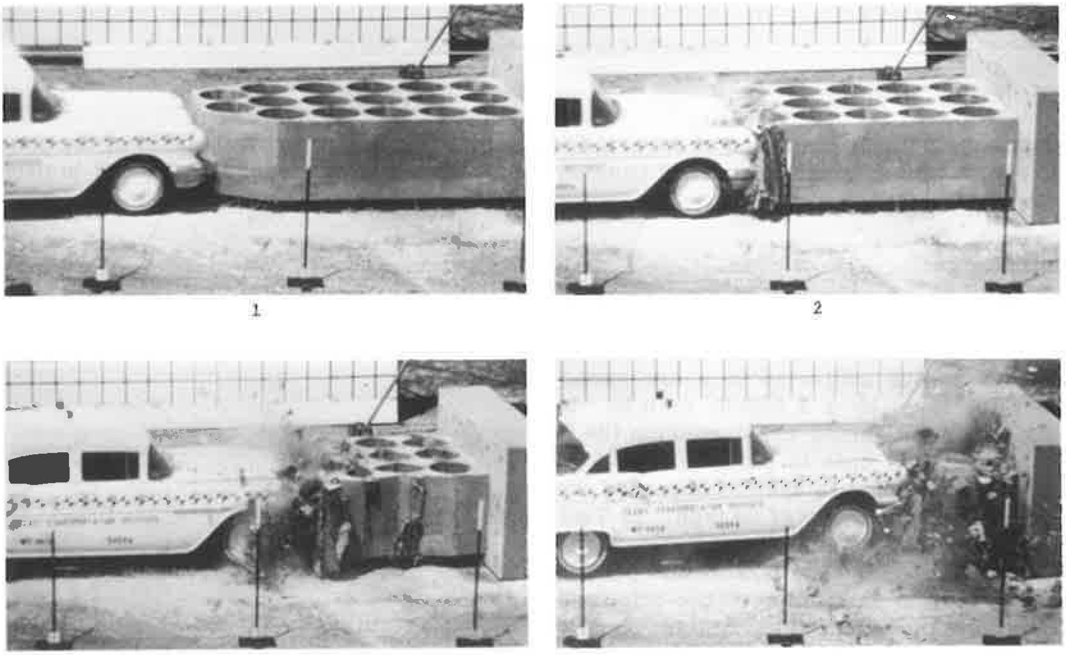


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Figure 7. Sequential photographs of Test A.

importance of the control of certain parameters in the fabrication of lightweight cellular concrete crash cushions. The compressive strength of the vermiculite concrete was increased to 71 psi and dimension B (Fig. 4) was increased to 2 in. The 24-1414 welded wire fabric was placed in the top and bottom of this barrier to eliminate the tendency of some portions of the barrier to scatter on impact. Because of these differences, the barrier was significantly stiffer than the previous barrier tested and a deceleration level of 10.3 g was observed. This corresponds to an average stopping force of approximately 33,000 lb. Overhead sequence photographs of this test are shown in Figure 8.

Based on the results of the first two tests, a third barrier (Fig. 5) was designed and tested that incorporated estimated stopping forces varying from 13,000 to 33,000 lb. The first 12 ft of barrier, with a predicted stopping force between 13,000 and 20,000 lb, would result in the deceleration of a 2,000-lb vehicle traveling 60 mph at a deceleration level slightly less than 10 g. The next 12 ft of the barrier, with 6 ft at a predicted 25,000 lb stopping force and 6 ft at 33,000 lb, would provide the necessary additional stopping force to decelerate a vehicle traveling 60 mph and weighing as much as 4,500 lb. This barrier was tested with a 4,560-lb vehicle traveling 63.6 mph, impacting head-on (Fig. 9). The estimated crushing force levels from photographic data show that the predicted stopping forces were fairly accurate. The vehicle was stopped in 21.4 ft at an average deceleration of 6.3 g, which means an average stopping force of 28,700 lb.

The final test, which was included for comparison purposes, was of a vehicle weighing 3,270 lb impacting a rigid wall at 53 mph. The average deceleration was 25 g and the stopping distance of the vehicle's center of gravity was 3.82 ft. The total vehicle residual crush was 3.25 ft.

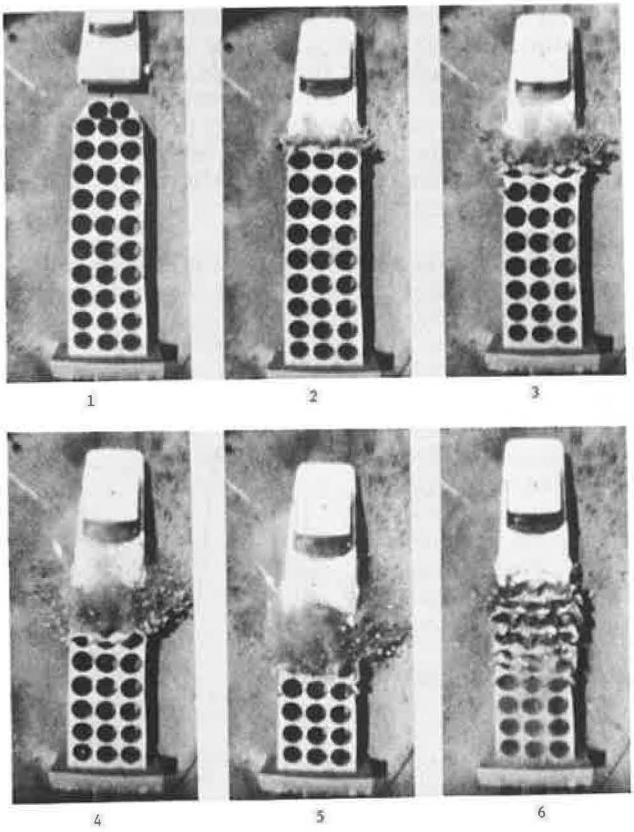

Figure 8. Overhead sequence photographs of Test B.

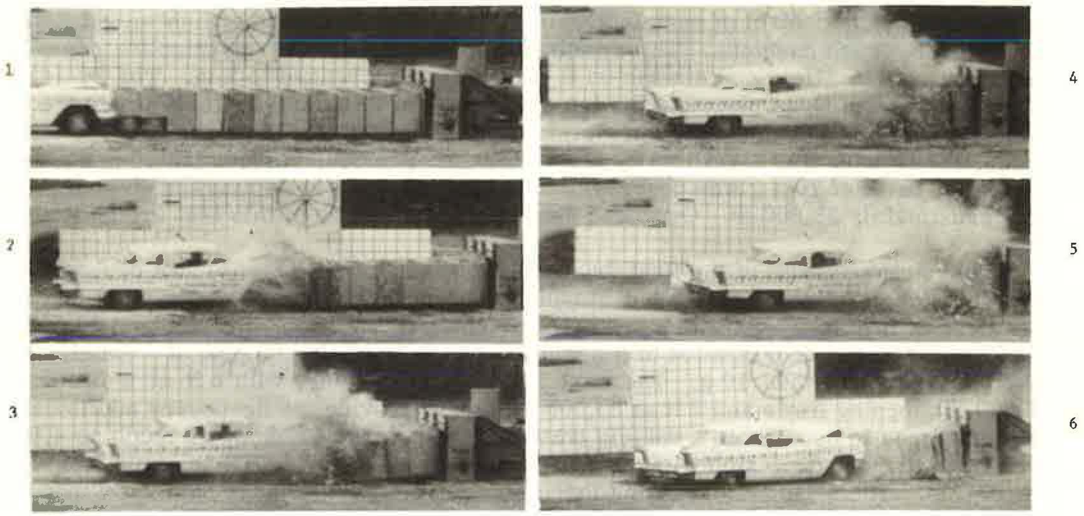

Figure 9. Sequential photographs of Test C.

A comparison of the severity of these crashes is given in Table 2 by the attenuation index. The maximum and average decelerations that would have been experienced by each vehicle had it struck a rigid barrier (for example, Test D) are calculated using accepted theory (2). The attenuation index is the ratio of the test maximum or average deceleration divided by the rigid barrier maximum or average deceleration respectively. The theory is an empirical generalization for all types of vehicles based on the particular vehicles tested by Emori, and could not be expected to give accurate decelerations for each vehicle tested. If the theory had accurately predicted the test decelerations, the attenuation index shown for this test would have been 1.0. The attenuation indexes for the three lightweight cellular concrete crash cushion tests show that the impact is approximately one-fourth to one-third as severe as it would have been had the vehicle struck a rigid barrier.

In Text A, only superficial sheet metal damage was sustained by the vehicle. The radiator was not moved with respect to the frame of the vehicle during the impact. In Test B, considerably more sheet metal damage was done to the vehicle and the radiator was moved back far enough to encounter the fan blades. However, the vehicle was driven away from the scene of the crash after the fan belt had been removed. In Test C, again only superficial sheet metal and some bumper damage was sustained. Test D (the immovable wall) resulted in the total and irreparable destruction of the vehicle.

Another way to demonstrate the differences between encountering a rigid obstacle and colliding with a crash cushion can be seen in Figure 10. Here the deceleration vs. time curves are given for the rigid wall test and for the last concrete crash cushion test. The crash cushion acts

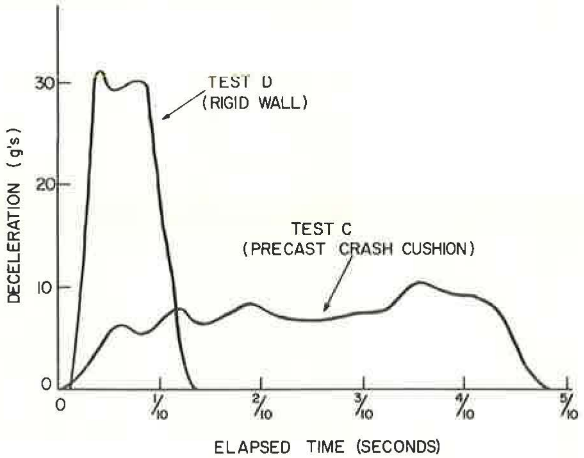

Figure 10. Comparison of decelerations.

to distribute the deceleration of the vehicle over a period of time that is approximately 5 times as great as that required to stop the vehicle when it encounters a rigid obstacle. The result is the significant lowering of the deceleration level indicated by Figure 10.

CONCLUSION

The lightweight cellular concrete crash cushion has been shown to be extremely effective in decelerating a vehicle during a head-on crash. Although side-angle hits have not been conducted, it is expected that further testing will show the acceptability for this collision condition also. This estimate is based on the acceptable reaction of the Modular crash cushion (3) composed of 55-gallon steel barrels, which functions in a very similar way. All tests show deceleration levels within the tolerance limits of restrained humans. The lightweight cellular concrete crash cushion can be installed by one of two methods by semi-skilled laborers. The formwork can be placed in the field, and a local vermiculite applicator can supply the necessary concrete; or the precast modular construction method can be used. The estimate of cast-in-place construction cost, including all materials and labor, is $800 per installation. Using the modular construction technique, considerable savings should be realized by mass production.

Close quality control should be exercised on the geometry of the attenuator and on the vermiculite concrete. Control of batch proportions and unit weight will give predictable crushing strengths. Replacement of segments of the crash cushion can easily be accomplished after a collision. For a cast-in-place cushion, the crushed material can be removed, that portion of the barrier re-formed, and fresh vermiculite placed in the necessary areas. Fast-setting cement will alleviate the problem of curing time. For the precast cushions, the three-tube modules weigh approximately 250 lb, and could therefore be handled easily by four men. The modules that have been crushed during a collision can be unbolted, removed, and new modules slipped into place. This refurbishment could be accomplished during a low-density traffic period.

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