

Foamed, Fiber-Reinforced Concrete as A Fragment Collecting Medium

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ABSTRACT

Foamed, fiber-reinforced concrete or shock-absorbing concrete (SACON) has been used successfully for years in structures designed for grenade and live-fire training exercises. The cellular structure of this type of concrete permits incoming bullets and fragments to bury themselves in the concrete without producing ricochets. Recent work on using foamed concrete in firing ranges has also shown that thick blocks of SACON can resist penetration from fragment impacts that occur at a single point beyond what might be predicted based on single projectile penetrations. Thick blocks of SACON when attacked with a weapon, such as the M16A2 rifle, firing multiple rounds into the same point develop pockets of dense bullet debris at the impact point that resist further penetration but do not produce ricochets. Low-density, steel fiber-reinforced SACON blocks showed a reduced rate of penetration compared to polypropylene fiber-reinforced blocks of comparable density. Three-shot bursts of automatic fire produced penetration rates that were similar to those produced from three rounds fired as single shots. Dust produced from the blocks during shooting contains only minor amounts of metal from impacting bullets. The concentrated fire on a small arms range when directed at target area small enough to contain the debris in a compact mass may produce so little penetration that SACON can continue to be a useful, fragment-retaining barrier beyond the service life that would be predicted from the penetration depth observed for the initial shot.

INTRODUCTION

SACON is a foamed, fiber-reinforced concrete that was originally developed by the U. S. Army Corps of Engineers as a shock-attenuating medium for use in protecting instrumentation in explosives testing (Hoff, 1967, 1971). Variations in this material were developed for use in constructing enclosures for training with live ammunition and hand grenades (Denson et al. 1984).

Currently interest in SACON has centered around its potential use in trapping bullets fired down range at small-arms training facilities (Fabian and others, 1996). At many of these training ranges, the bullet impacts are restricted to a relative small area directly in front of the shooter and thousands of rounds can impact within an area that may be less than one meter square. These rounds must be intercepted by a medium that will provide safe containment (even for tracer rounds), produce no ricochets and maintain training realism by presenting the shooter with a scene that is consistent with what might appear in a battle area.

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A testing program was undertaken to determine the effects of concentrated fire (single rounds and automatic fire) into SACON blocks made with different densities and different types of fiber reinforcement. Data were needed in order to determine the ability of the materials to contain bullet debris and to determine the effects of an accumulation of bullet debris on the ability of a SACON barrier to absorb additional bullets without producing ricochets.

DESIGN OF THE TEST PROGRAM

SACON functions as a friction-type trap where the incoming projectile loses energy by crushing the cellular structure of the concrete. Bullets traveling the same path into the concrete can presumably produce progressive damage as the impact point moves deeper into the thickness of the concrete. Firing a weapon into the same hole should produce penetration of the barrier with fewer rounds being expended, than had the bullet impacts been distributed over a broader area of the surface of the SACON barrier. The test program was developed to produce the maximum number of bullet-on-bullet impacts in order to produce deep penetration and to examine the effect of embedded bullet debris on ricochet or back splatter.

The most common weapon used in small-arms training is the M16A2 rifle firing the 5.56-mm NATO Ball M855 round. The M16A2 has a muzzle velocity of 990 to 1,000 m/s and a cyclic rate of fire in the "burst" mode of 700 to 900 rounds per minute (Jane's Information Group, 1998). The testing was done with a police version of the M16A2 mounting a standard issue barrel. The test rifle was equipped with telescopic sights and with a trigger-and-sear mechanism that allowed shots to be fired singly or in three-shot bursts. All firing was done from a clamped rest at a distance of 5.5 m. The entry hole in the block was typically less than 10 mm in diameter for 10 rounds.

The M855 round has a bullet that consists of a brass (copper-zinc alloy) jacket over a steel penetrator and a lead alloy (lead-antimony) slug. Each bullet is designed to contain 1.30 g of copper alloy, 0.65 g of steel and 2.07 g of lead alloy; for a total mass of 4.02 g. On impact the jacket is often shed, the steel penetrator remains intact, and the lead alloy breaks into small fragments. The test procedure employed in this evaluation produced compact masses of bullet debris that consisted of clusters of penetrators tightly packed together with fragments of copper jackets and lead slugs.

The SACON bullet-trapping blocks used were cast from foamed concrete (or mortar) reinforced with steel or polypropylene fiber. Details on the preparation of SACON are presented in Fabian and others (1996). Four types of blocks with densities ranging from 800 to 1,240 kg/m³ were tested. Characteristics of the blocks used are summarized in Table 1. Each test block was set up in a Plexiglas enclosure with a bullet port that was large enough to permit the bullet to travel to the test block, but material knocked from the front of the block was trapped in the enclosure and could be collected. All blocks were of sufficient thickness to withstand 10 shots without being penetrated.

Table 1. Properties of SACON Used in this Investigation		
Block Series	Density (Kg/m ³)	Unconfined Compressive Strength (MPa)
70 steel	1,236	2.8-3.5
60 steel	1,080	2.7-2.9
50 steel	915	2.1-2.4
50 polypropylene	800	2.1-2.4

The apparent depth of penetration of a bullet into a block was measured by inserting a 4-mm diameter steel rod into the bullet entry hole and measuring the distance from any obstruction in the hole to the surface of the test block. Measurements involved an uncertainty of approximately 3 mm. The bullet from an intact M855 round is 23 mm long. If a bullet remained intact, the position of the front of the bullet was 23 mm deeper in the block than the apparent depth of penetration. In most cases the bullets fragmented and the apparent depth as measured represents the best estimate of the depth of the deformed bullet or the mass of bullet debris.

Two test series were undertaken, one in which the shooter fired 10 rounds as single shots, and a second in which the shooter fired 9 rounds as three 3-shot bursts. The M16A2 can fire a single, three-round bursts in approximately 0.3 sec. The apparent depth of penetration was measured after each single shot or after each 3-shot burst. The results of the first 9 single shots (considered as three 3-shot groups) were compared to the results of three 3-shot bursts to see if the rapid succession of bullet impacts from a burst produced a ricochet or changed the rate of advance of the impact point into the block.

Fine fragments of concrete and bullet debris were observed in the test block enclosure. During one shooting sequence (test on Block 70 steel A), the dust expelled from the block was collected after each of 11 single shots was fired into the block. Each dust sample was weighed and analyzed for lead and copper using x-ray fluorescence to determine how much fragmental metal from the impacting bullets was ejected from the block. Block 70 steel A was broken apart after the shooting was completed. Bullet fragments were recovered and examined to determine if large bullet fragments were surviving the impacts.

RESULTS

Figure 1 shows the apparent depths of penetration measured in three different densities of steel fiber-reinforced SACON test blocks after each of 10 single shots was fired into a point on the block. Note that the depths of penetration do not increase consistently. Identically prepared test blocks (70 steel A and B) varied widely in the apparent depth of penetration, even on the initial shot. The shallowest hole produced by the initial round is 76 mm (Test Block 70 steel A). In these tests the second shot impacting the same point never produces a depth of penetration that

exceeds the depth produced by the initial shot hitting that point. The least dense block (50 steel) showed the deepest penetration after the 9th or 10th bullet impacted; but, the denser blocks showed deeper penetration than the Block 50 steel earlier in the shooting sequence.

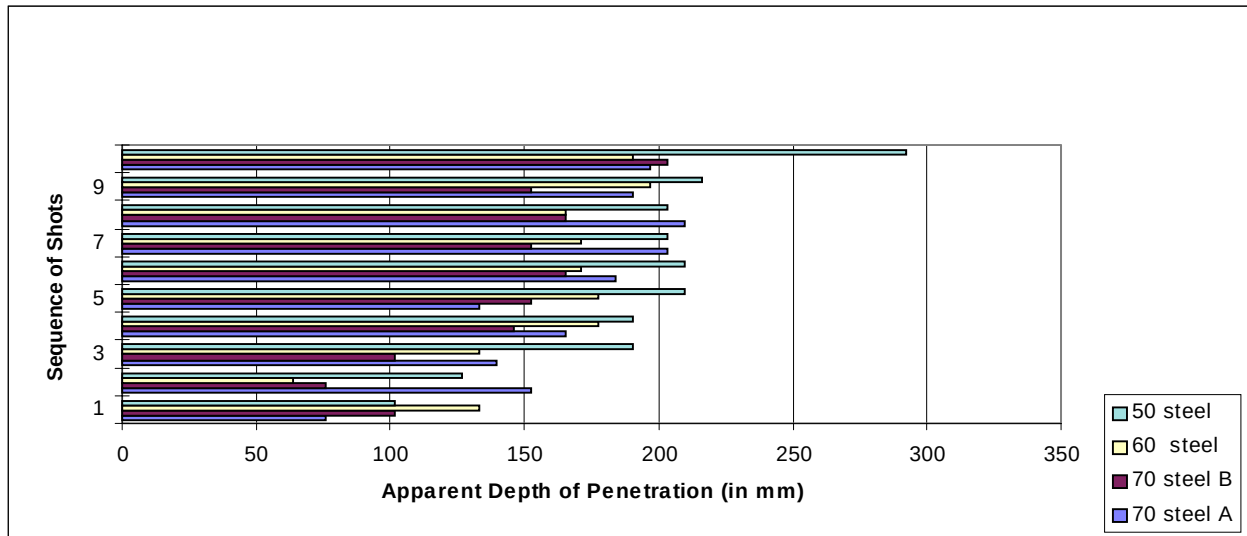


Figure 1. Comparison of the penetration of 10 single shots in four samples of SACON with steel fiber reinforcement.

Figure 2 shows the apparent depths of penetration for a low-density, steel fiber-reinforced block (Test Block 50 steel) and for a low-density, polypropylene fiber-reinforced block (Test Block 50 polypropylene). After 10 shots were fired the hole in the polypropylene-reinforced block was approximately 30 percent deeper than the hole in the steel-reinforced block.

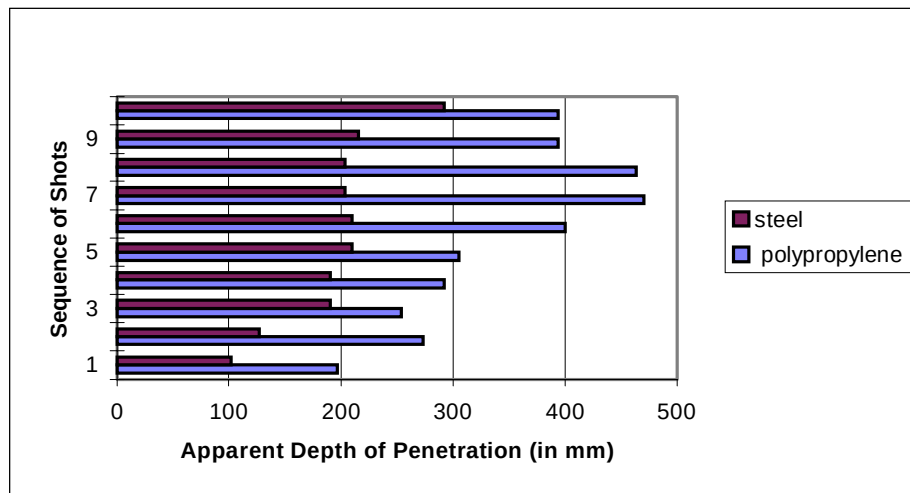


Figure 2. Comparison of the penetration of 10 single shots in samples of 800 and 915 kg/m³ (Series 50) SACON blocks with polypropylene fiber and steel fiber reinforcement.

Figures 3 through 6 shows the apparent depth of penetration for nine single shots and three 3-shot bursts. There was no consistent effect at all densities from automatic fire. Shots at the high-density blocks showed the nine single shots produced deeper penetration than the same number of shots fired as bursts. In all other test blocks, the bursts produced penetration that was equal to or greater than that observed with single shots. In all of the tests, no ricochets were observed and in all cases the initial three shots produced greater penetration than later 3-shot groups (single shots or bursts).

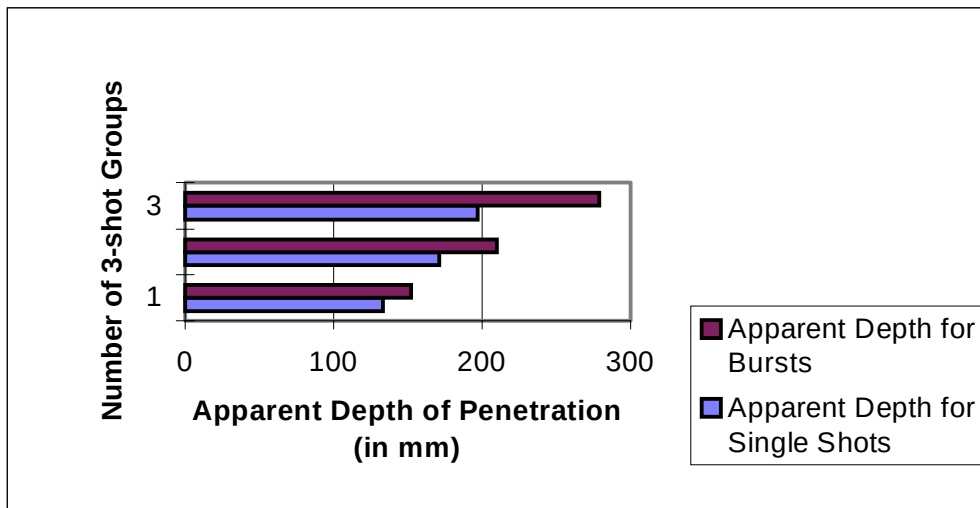


Figure 3. Comparison of the penetration of 9 single shots and three 3-shot bursts in samples of 1,236 kg/ m³ (Series 70) SACON blocks with steel fiber reinforcement.

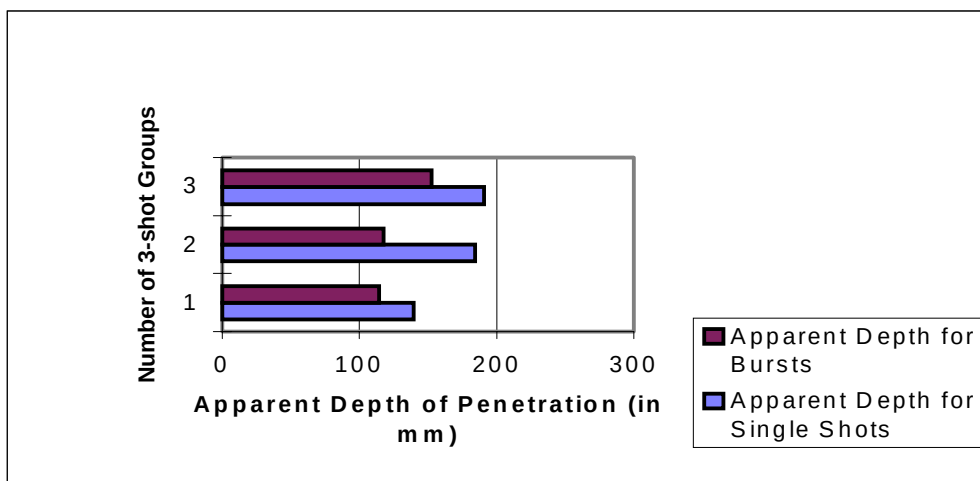


Figure 4. Comparison of the penetration of 9 single shots and three 3-shot bursts in samples of 1,080 kg/m³ (Series 60) SACON blocks with steel fiber reinforcement.

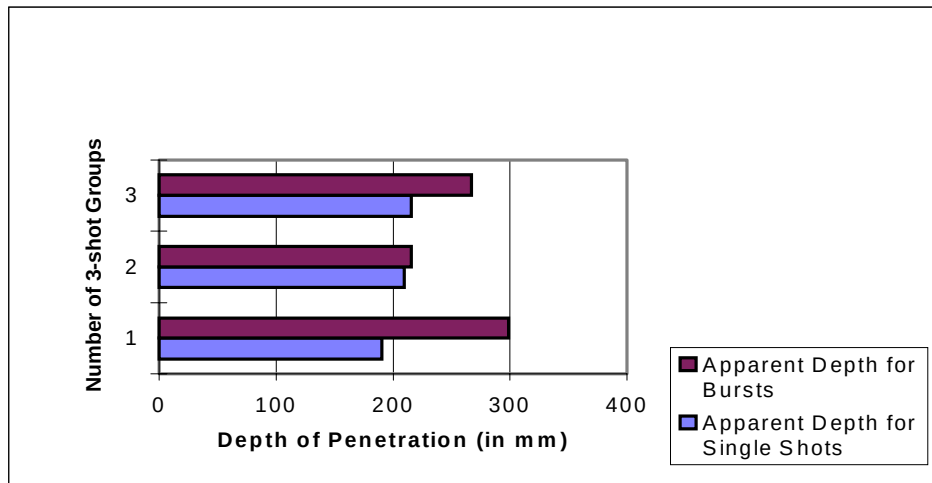


Figure 5. Comparison of the penetration of 9 single shots and three 3-shot bursts in samples of 915 kg/m³ (Series 50) SACON blocks with steel fiber reinforcement.

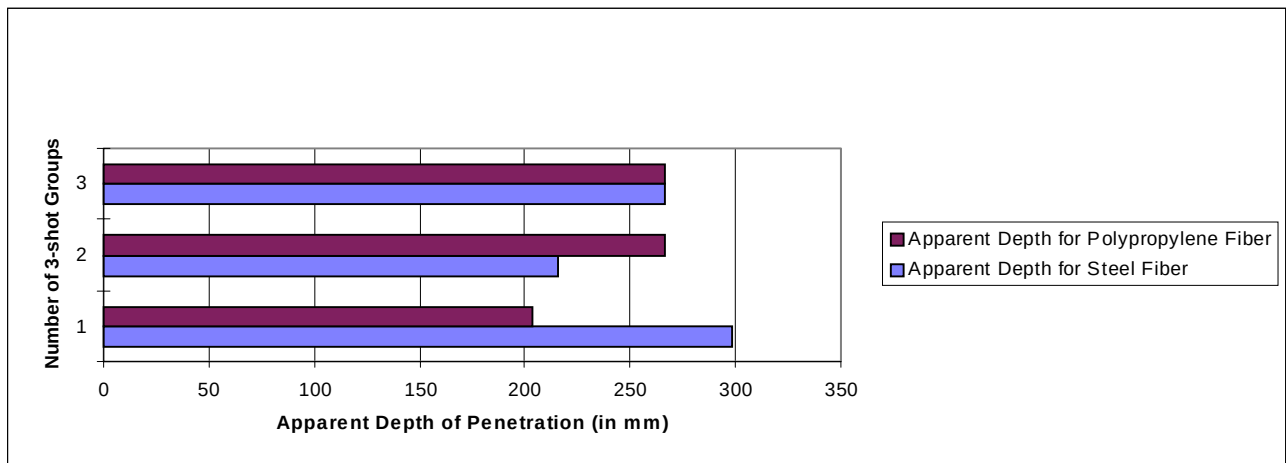


Figure 6. Comparison of the penetration of three 3-shot bursts in samples of (915 kg/m³) SACON blocks with steel fiber reinforcement and (800 kg/m³) SACON blocks with polypropylene fiber reinforcement.

Table 2 summarizes the data on the fine fragments (dust) ejected from Block 70 steel A after each of 11 shots (with 10 bullet-to-bullet impacts) was fired into the block. Less than a gram of dust was ejected after each shot. The highest concentration of lead observed was 3.41 percent; copper was found at concentrations as high as 0.80 percent. For all 10 bullet-to-bullet impacts, the average amount of dust produced was 0.42 g/impact with an average lead content of

1.81 percent and an average copper content of 0.21 percent. The fine bullet fragments ejected from each bullet impact would amount to approximately 2 percent of the total debris. Each impact produces approximately 0.41 g of concrete dust and 0.01 g of fine bullet fragments. An average of 0.2 percent of the original 4-gram bullet escapes from the block when the bullet impacts the block and strikes another bullet during multiple impacts.

Table 2. Summary of Chemical Analyses of the Dust Collected after Each of 11 Rounds was Fired			
Round Fired	Mass of Dust (g)	Lead Content (%)	Copper Content (%)
1	0.986	0.87	0.18
2	0.886	2.55	0.27
3	0.359	1.86	0.19
4	0.967	3.01	0.20
5	0.736	1.54	0.13
6	0.097	3.41	0.02
7	No dust produced	---	---
8	0.295	0.23	0.80
9	0.533	1.86	0.04
10	No dust produced	---	---
11	0.338	0.01	0.03

In all of the testing on Block 70 steel A, 17 single shots were fired into block. After the test firing, the block was crushed and the fragments were recovered. All of the 17 steel penetrators were recovered intact. The masses of the 10 largest fragments are given in Table 3. The largest fragment consisted of two partial bullets that were press together, none of the single large fragments was sufficiently massive to be an entire bullet.

Table 3. Masses of the Ten Largest Bullet Fragments Collected from Block 70 A		
Rank by Mass	Mass (g)	Description
1	4.20	Fragments of two bullets
2	3.79	J-shaped
3	3.46	J-shaped
4	3.43	J-shaped
5	2.83	Tip and jacket
6	2.81	Tip and jacket
7	2.68	Tip and jacket
8	2.09	Tip and jacket
9	1.98	Tip and part of jacket
10	1.92	Tip and part of jacket

DISCUSSION

The important factors that influence the depth of penetration of a given projectile into porous, granular, cemented materials are strength and density of the target materials and the frontal surface area of the projectile. Penetration predictions are complicated because the bullet from the M855 round distorts and fragments badly on impact. Attempts to predict penetration of bullets into SACON using the PENCURV code were successful only when the fragments were treated as the projectile (Tom, Berger and Malone, 1996). Penetration predictions for high-speed projectiles ($> 1,000$ m/s) in porous concrete developed from the Poncelet equation were found to be satisfactory as long as the projectile did not deform (Wise, 1994). The Poncelet equation defines the interfacial forces, F , between the projectile and the target material as a function of the compressive strength, y , density, r , of the target materials and the velocity, v , and impact area, A , of the projectile.

$$F = ma = -(C_1y + C_2rv^2)A$$

where C_1 and C_2 are constants related to the specific material. The $C_1 y$ term is the force acting to slow the projectile due to the strength of the target material. The $C_2 r v^2$ term relates to the friction or drag on the projectile due to the density of the target material. In the present investigation of the decreasing penetration due to bullet debris the only factor that is changing is the density of the target at the impact area. The increased density has two effects; it increases drag acting on the projectile and also increases the deformation of the projectiles striking the impact area. Penetrations from successive impacts should be a function of the density increase although the drag effect may be overshadowed by the deformation that the bullet debris (especially the steel penetrators) can produce on incoming bullets.

For the purposes of estimating the approximate effect of impacts from successive rounds, it is assumed that all of the target materials and all of the bullet debris would remain in the target and would form a denser mass that would become the target medium for the next incoming bullet. The foamed concrete is assumed to collapse completely and compact to a material that has the density of the composite granular materials (quartz sand, iron fiber fragments and portland cement grains). All of the solid volume of porous concrete in front of the bullet is assumed be compressed ahead of the bullet. The new dense material is assumed to be a homogeneous medium with the same strength characteristics as the surrounding undeformed material. Where the apparent depth measurements showed no increase in depth it is assumed that the depth of penetration increased enough to accept the volume of the bullet.

Data from Block 70 steel B was developed as an example case in examining effectiveness of using the postulated increased density for predicted the approximate depth of penetration from successive bullet impact on the same point. If compacted from a porous solid to a compact solid (no voids) the density of the SACON used in Block 70 steel B should rise from 1.17 g/cm³ to 2.95 g/cm³. The bullet in the M855 round has a mass of 4.0 g, a volume of 0.40 cm³ and a diameter of 5.56 mm. The density for the bullet is approximately 9.8 g/cm³. If it can be assumed that as a first approximation the depth of penetration is a simple inverse linear function of the density then the depth of penetration should be predicted by assuming that doubling the density will reduce the penetration by a proportional amount. Figure 7 shows a plot of the calculated penetration produced by successive impacts and the apparent depth of penetration observed. The penetration from the first shot fired is reduced in successive shots as the inverse of the proportional density increase that is produced by the bullet and compacted SACON. For all rounds after the first round:

$$EDOP = ID + ID(r_{int}/r_{new})$$

where: EDOP = Estimated depth of penetration produced by the shot

ID = Initial depth of penetration

r_{int} = Initial density

r_{new} = New composite density at impact point.

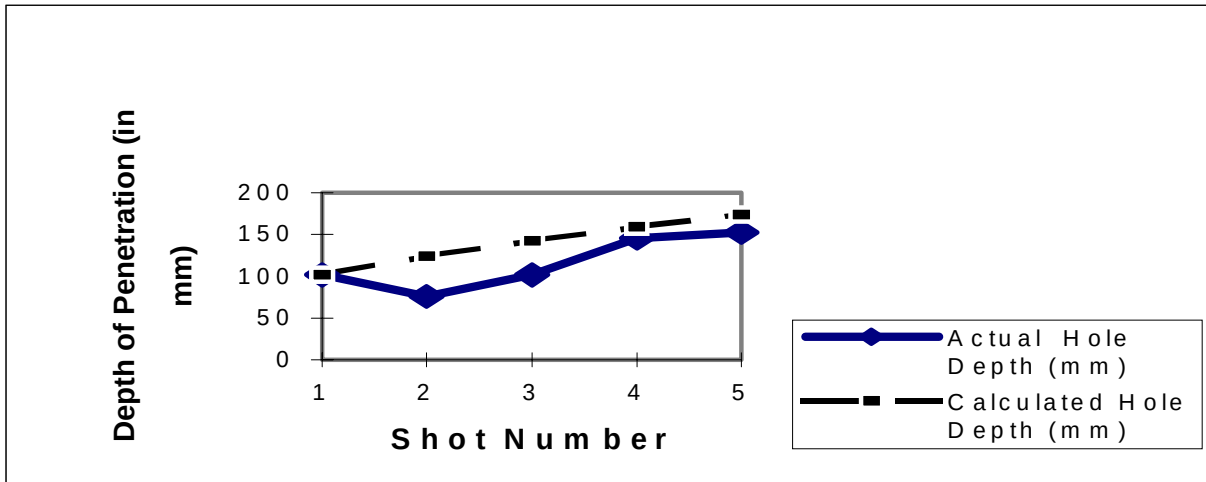


Figure 7. Comparison of the measured apparent penetration of 5 single shots in samples of Series 70 SACON blocks with steel fiber reinforcement and the predicted penetration based on density increases.

This approximation is only useful for the first few rounds because the greater density of the bullet compared to packed SACON will cause r_{new} to approach the density of the bullet (9.8 g/cm^3) quickly. When the pocket of debris becomes a mass of bullet fragments, the apparent depth of penetration will remain nearly the same shot after shot and the incoming bullets will fragment on the dense mass. If the test block is not penetrated through its full thickness, a cavity will form as bullet fragments cut away the SACON around the impact point inside the block.

CONCLUSIONS

The results obtained in this project indicate:

- SACON target blocks of densities ranging from 800 to $1,240 \text{ kg/m}^3$ can withstand multiple bullet impacts from the M16A2 rifle firing the M855 round at the same point without producing ricochets.
- A three-shot burst fired from the M16A2 in automatic fire-mode produces approximately the same apparent depth of penetration in SACON as would be observed from three rounds fired as single shots.
- In low-density (800 kg/m^3) SACON blocks, steel fiber reinforcement produced a reduced level of bullet penetration compared to polypropylene fiber reinforcement.

d. A SACON target block with a density of 1,240 kg/m³ will release very little (0.2 percent by mass) of the bullet debris created by multiple bullet impacts on the same point.

e. Multiple rounds fired into the same bullet hole increase the density at the impact point in the test block and reduce the penetration produced by successive bullet impacts. An estimate of the penetration of the first few bullets fired can be developed by assuming that penetration of each successive bullet will be reduced from the initial penetration depth by a factor that is the ratio of the original density of the block to the calculated density of the debris at the impact point in the block.

f. Predicting the depth of penetration produced by multiple bullet impacts will always be complicated by the lack of uniform, homogenous densities in the debris, the lack of any technique for measuring the compressive strength of the debris mass and the effect of the debris on the distortion and fragmentation of impacting bullets.

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