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Robert Paul Cole
University of South Florida

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Ballistic Penetration of a Sandbagged Redoubt Using Silica Sand and Pulverized Rubber of Various Grain Sizes

by

Robert Paul Cole

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering
College of Engineering
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Major Professor: Stuart Wilkinson, Ph.D.
Nathan Gallant, Ph.D.
Rasim Guldiken, Ph.D.

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Crushing

Dedication

This research is dedicated to all the people who have supported me through the duration of my student life. To my parents, Robert Eugene Cole and Catherine Anne Mckendree, who have given, through strong nourishment, the inspiration to design creatively, I owe my existence. To my friends, who have given me the gift of friendship (even when my responsibilities inhibit my ability to return the favor), I owe greatly. To my fiancée Lauren Valdez, who has been with me through the toughest parts of it all, and her parents, Dennis and Bonnie, who put up with me, I owe all my love.

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I would like to acknowledge Dr. Stuart Wilkinson, who helped get this project underway, and who guided me through the entire process.

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Abstract

The basis of this work is to find how varying the grain size of materials contained in sandbags (sand and crumb rubber) effects the ballistic penetration of the projectiles from both the 7.62x39mm (308-short), and 9mm Luger cartridges. The sandbags were stacked in a pyramidal stacking configuration according to military specifications in order to simulate a section of a sandbag barrier or redoubt as would be seen on the battlefield. The projectiles were fired at the targets, and the velocity and penetration data was recorded. The results concern both military and civilian applications alike. The 7.62x39 round was found to experience more fragmentation as grain size increased, and was also found to have, on average, the least amount of penetration into the largest grains. The 9mm round was found to suffer negligible deformation in all of the various sizes of materials, and when fired at the two types of materials, showed a steady trend of decreasing penetration depth with increasing grain size. The sand had a wearing effect on the projectiles leaving them scared or fragmented and deformed while the rubber kept the rounds in pristine condition.

Chapter 1: Introduction

The initial hypothesis is that the penetration of a projectile into granular matter decreases with increasing grain size. This is reached by taking the extremes of the spectrum into consideration. For instance, if the grains are enlarged to the point that the projectile is, in effect, impacting a solid rock surface, the penetration will be considerably less if there is penetration at all. On the other hand, if the grain size is decreased to the point that the granular matter is basically single molecules, there will be no crushing of grains (totally eliminating one mechanism that aids in stopping the projectile), and also creating a less uniform packing order (hence reducing effective density), which acts to reduce the pressure that stops the bullet, and therefore causes an increase in the penetration depth. With that said, the opposite ends of the spectrum clearly point to a decrease in penetration with an increase in grain size.

1.1 Ballistics

The field of ballistics is of high importance with regards to national defense and security. It becomes important to predict the outcome of an impact between any possible projectile and target; whether it is complete destruction of an enemy tank on the battlefield or the complete absorption of energy from a handgun bullet by a police officer’s bullet-proof vest. The problem is there are an infinite number of possible impacts and very little data that can describe materials in these high-strain-rate conditions [1].

In the field of ballistics, there are three main areas of importance: the path of the projectile from rest to the exit of the barrel or tube, known as interior ballistics, the flight of the projectile to the target, or exterior ballistics, and the final stoppage of the projectile in the target called terminal ballistics [2].

1.1.1 Interior Ballistics

Interior Ballistics is a highly complex empirical science which owes its understanding to the analysis of an incredible bulk of data. There are many factors that affect a projectile's acceleration through the barrel, such as: projectile mass and materials used, mass of propellant, length of barrel, tightness of fit between projectile and barrel, and also the number of twists in the rifling of the barrel [2]. This multitude of variables, along with the variance of any single component due to manufacturing, makes analytical formulation nearly impossible.

1.1.2 Exterior Ballistics

The flight of the projectile from barrel to target is stated as exterior ballistics. This is where the projectile is traveling through air at some velocity. Fluid dynamics is applicable to this area of ballistics and it is, for the most part, well understood mathematically and easily modeled on computer. There are few factors that control a projectile's flight; projectile shape and velocity, relative wind velocity, and gravity dominantly determine the path after launching the projectile. Gravity is considered to remain constant in most cases, as it is for this study, and for the mediums in which projectiles travel, typically air, the properties are well understood and predictions are possible with great accuracy. The only practical problem confronted in battlefield scenarios is the variation of wind direction over long distances, which concerns snipers and other long distance shooters who deal with these dynamic conditions.

1.1.3 Terminal Ballistics

The final deceleration of the projectile as it enters the target is known as terminal ballistics. This is sometimes considered an extension of exterior ballistics with a much denser medium that has far greater structural integrity than air. There are many different targets (ballistic gelatin, Kevlar®, steel, etc.) that are either under research currently, or were recently published [2, 3, 4, and 5], detailing the most recent efforts to understand, and quantify analytically the mechanisms involved such that predictions can be made for the penetration in some of the most common materials. There are many factors determining the path, in time and space, a projectile will take as it travels through a target media, and the analysis is “formidable”. Without good statistical data on a given projectile/target-material combination (especially at high strain-rates) analytical analysis is impossible [1]. The majority of study is performed through experimental analysis combined with advanced modeling techniques.

1.2 State of the Science

Currently there are two modes of terminal ballistics research (involving granular matter) trying to reach a connection. There is the experimental approach which concerns itself with idealizing the conditions of the projectile and granular matter by using a very specific projectile shape and orientation of particles (or cylinders in the case of 2-D experiments), then observing by fast video photography the effects produced by projectile penetration (as in [6]). There is also the simulation method which contains deeply involved computer code that calculates interactions from one moment to the next, and determines what effects are caused through the duration of penetration (as in [7]).

1.2.1 Classification of Granular Materials

Granular matter comes in many forms from quartz and silica sand to exotic man-made silicon carbide powders. In order to classify granulate materials by grain size, two major standards were developed known as the US sieve size and the Tyler Equivalent. The Tyler Equivalent corresponds to the number of openings in the screen per linear inch, while the US sieve size is a number without any physical meaning. The two are very close, and in some cases identical, but vary slightly from each other over the range of interest. Most sand falls between 6 and 80 US sieve size, while finer sand, such as silt, is above 80, and coarser media such as aquarium pebbles is below 6. The range of size for a given sample is determined by what sieve the matter passed through and what sieve it was retained by, or, for example, 60/80 for a sample that passed through a 60 mesh sieve and was retained by an 80 mesh sieve.

The main issue that comes from granular matter is the complex nature of reactions of the grains. Grains of sand found in nature are of varying shape and size as shown in Figures 1 and 2 below. However, due to the current limitations of modeling and computing power, by and large, the grains are idealized as perfect spheres.

Figure 1 Variation of Roundness and Sphericity of Sand Grains[8]

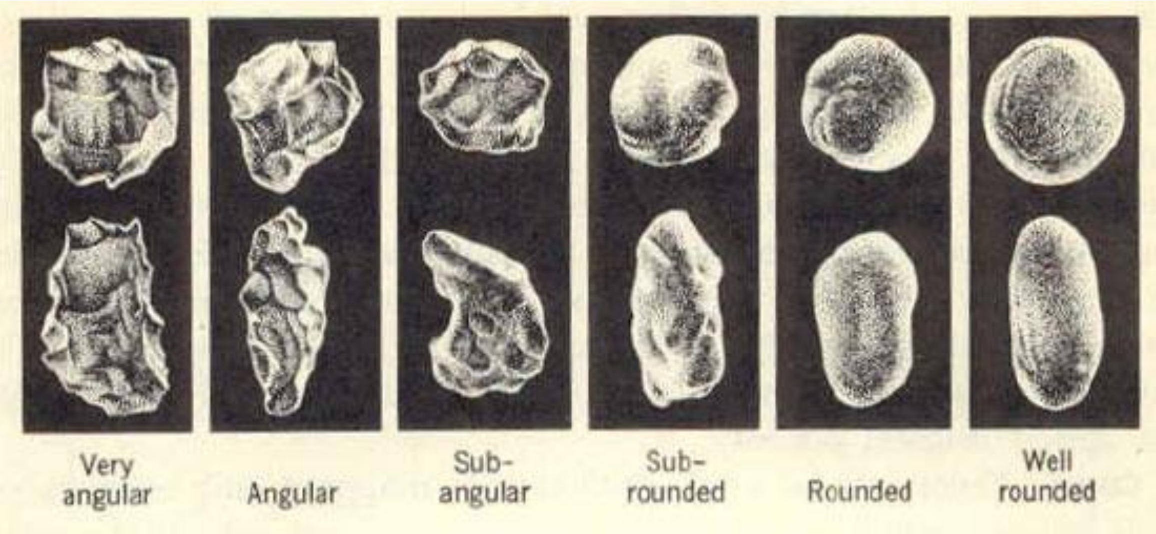


Figure 2 Classification of Sand Grain Roundness [8]

1.2.2 Limitations of Computer Simulations

The number of grains a projectile affects when encountering fine grained sandy media is on the order of 10^8. However, the number of grains currently feasible for use in computer simulation is on the order of 10^6, which limits both the size of the grains and the control volume cross-section that can be used [6]. With the advancement of computer science there is an ever improving ability to visualize and study the interactions of grains as projectile penetration occurs. This provides better understanding of the chain of reactions, but because the models do not have the ability to consider enough grains, or large enough control volumes, there is still disconnect between simulation and reality. Another major problem in defining granular penetration models is the definition of the boundary conditions, which is one of the most important aspects of the model.

Chapter 2: Literature Review

Ballistics is a very widely studied topic with a wide range of topic matter. For the following review, there are several areas of interest. There is some focus on first-hand battlefield knowledge for evidence of what scenarios are possible or probable, but there is also focus placed on the latest modeling and simulation techniques which allows reasonable assumptions of certain affects that are inherent when changing the grain size of the target material. It is evidenced through the timeline of research-material that no one cohesive theory defines the projectiles path, however the search for understanding is still underway.

2.1 Field Fortification

From the earliest of times there has been interest placed on the effects of a projectile colliding with another object and the invention of gunpowder has only generated more interest. The reasons for fortification are many, but protection from small-arms projectile impact is of interest here. On the battlefield, or in preparation for battle, there is generally minimal time to fortify. As history has shown, sandbags supply a tough and easily constructible barrier against most common rounds used in both rifles and pistols.

In [9], it is tabulated for the smaller rounds, the penetration depth that is achieved by a 154 grain musket round shot into sand at different distances. With “dry sand in bags” there was penetration from 6 to 7 inches (15-18 cm), “wet sand in bags” is said to have achieved a slightly greater depth of 7.5 to 8.5 inches (19-22 cm), and “loose damp sand" penetrated from 8 to 14 inches (20-36 cm). The sand used is said to be "fine, light-colored quartz" sand with a density of 86 lb/ft^3 (1378kg/m^3), but no indication is given to the average size of the sand grains. There is other target material referred to as "rammed earth", which is made of clay and sand, with reference to the penetration of much larger calibers such as the "18 pounder" and the "6 inch Howitzer". With the largest of calibers the penetration is said to have never exceeded 22 feet [9, and 10]. An interesting illustration (Figure 3, shown below) depicts the variation in the path of the projectile. Notice the immediate change in direction in the estimated path for one, and the change in orientation of another. These larger calibers are outside of the scope of this work, but the factors of scaling are of importance when considering the relative size of the projectile to the medium with which it reacts.

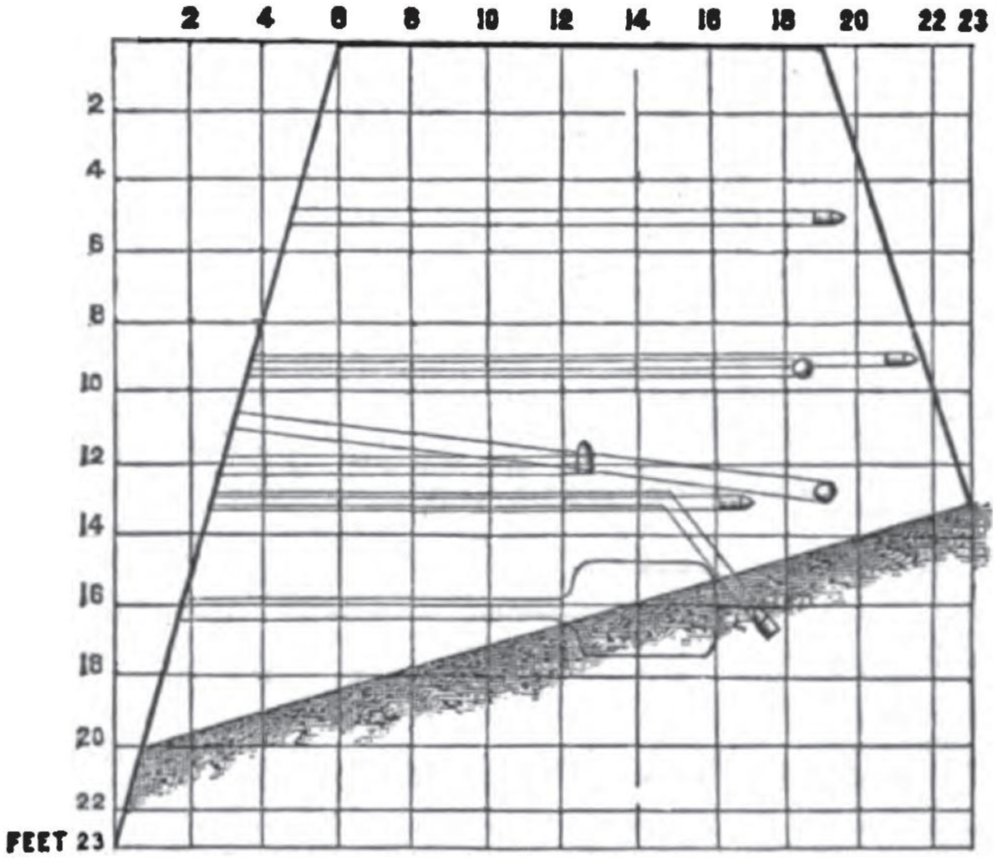


Figure 3 Cannon Penetration Paths [9]

As for field fortification in battlefield scenarios, the basic idea is build it bigger than needed, and if possible, the barrier should be at least twice the penetration depth of the round being defended against. The reasoning behind this is evident when considering the effects of not one, but multiple shots and the wearing effect it can have on a parapet [9].

2.2 Experimental Effects

Because penetration knowledge of an enemy's projectile is imperative for battlefield survival, the effects have been studied by engineers both soldier and civilian alike. There is clearly no better example for a target's reaction to a projectile than experimental study. Since the beginning of research in this area, when it is desired to know how a target material, such as human flesh, will react to a given round, it is typically easiest to find something similar, such as ballistic gelatin or a pig carcass, to test against [11]. In the same way, when someone wants to know how a certain composite reacts to projectiles, there is need to experiment.

Generally, when penetration is analyzed, a curve-fit of the data follows, and for various media and projectiles the coefficients vary, but for most cases, of impact with sand, the data has been fit to a second order equation, such as Equation (1) first proposed by [12],

$$-dv/dt = \alpha v^2 + \beta v + \gamma \tag{1}$$

Equation (1) can also be written as shown below in Equation (2) without linear velocity contribution to acceleration.

$$m\frac{dv}{dt} = -(av^2 + b); v(0) = V_0 \tag{2}$$

Here, a and b are empirically computed constants. However, it has been shown that in the case of ballistic sand studies, these second order equations do not adequately model the acceleration or easily forecast penetration depth [1, 2, 11, 13, and 14]. Equation (3) is given by [2] for “structurally firm viscous materials (sand, loose soils, etc.)” as shown below.

$$b^2S = cLn(c + bV) - bV + d \tag{3}$$

Here, S is the penetration depth, V is the projectile velocity, b and c are empirically determined coefficients and d is a constant. In order to predict the depth of penetration, currently, the coefficients must be obtained for the given sample. This calls for testing between the media and the projectile, which will then allow intermediate velocity penetration to be calculated.

2.3 Dynamics and Predictions

There are multiple mechanisms for projectile penetration as shown below in Figure 4.

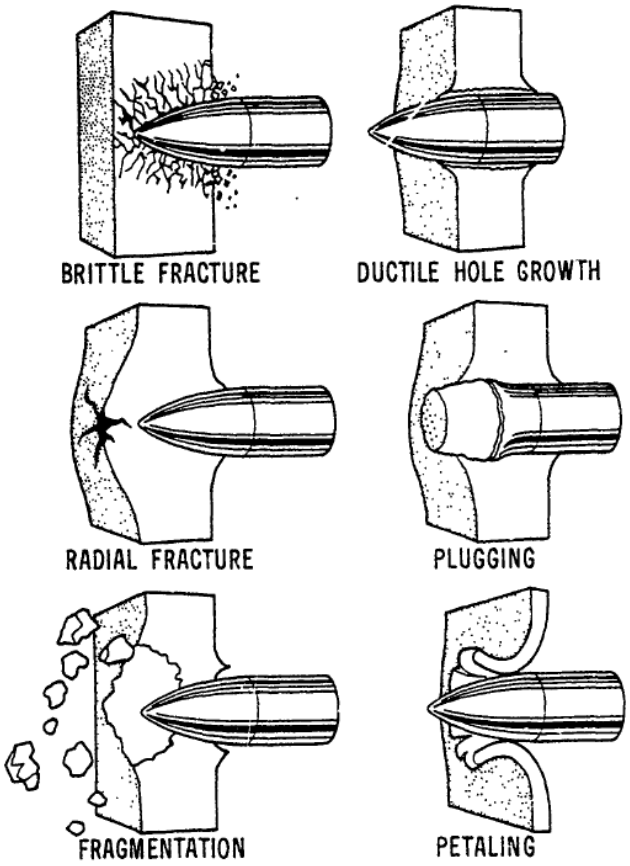


Figure 4 Modes of Target Failure for Solid Targets [1]

During penetration of a projectile into a container of sand, combinations of the different modes above can be present along with crushing of sand particles, and compression of sand particles (see Figure 5 for stress strain analysis of dry quartz sand size 14/40 sieve test sample).

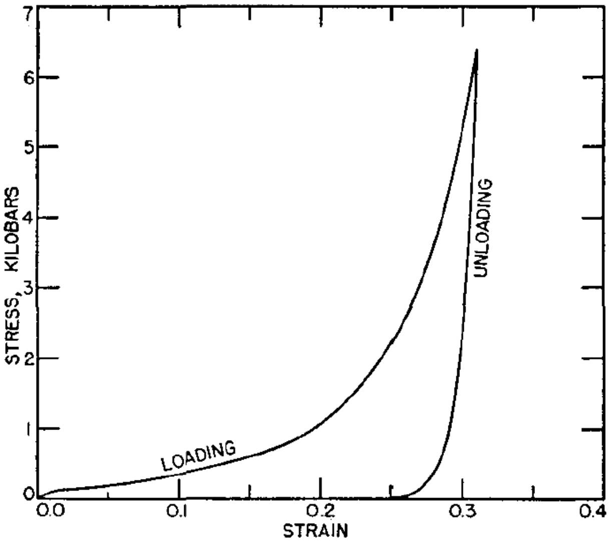


Figure 5 Stress Strain Diagram for a Given Sample of Sand [12]

The area between the curves represents the work done on the sample and signifies the inelasticity and compressibility of the sand [12]. It becomes extremely important to characterize the properties of the sand before and after experimentation to fully understand the mechanisms and their effects in the media. There is an infinite number of sand-size/moisture combinations that are present in nature and an overall shortfall of experiments to describe such variation [1, 12, 15, 16, and 17].

2.3.1 Identifying Properties of Target Material

As previously stated, it is imperative to characterize the properties of the media to fully understand the transient displacement of the projectile in the media. Reference [18] has a good review of penetration studies for determining these properties.

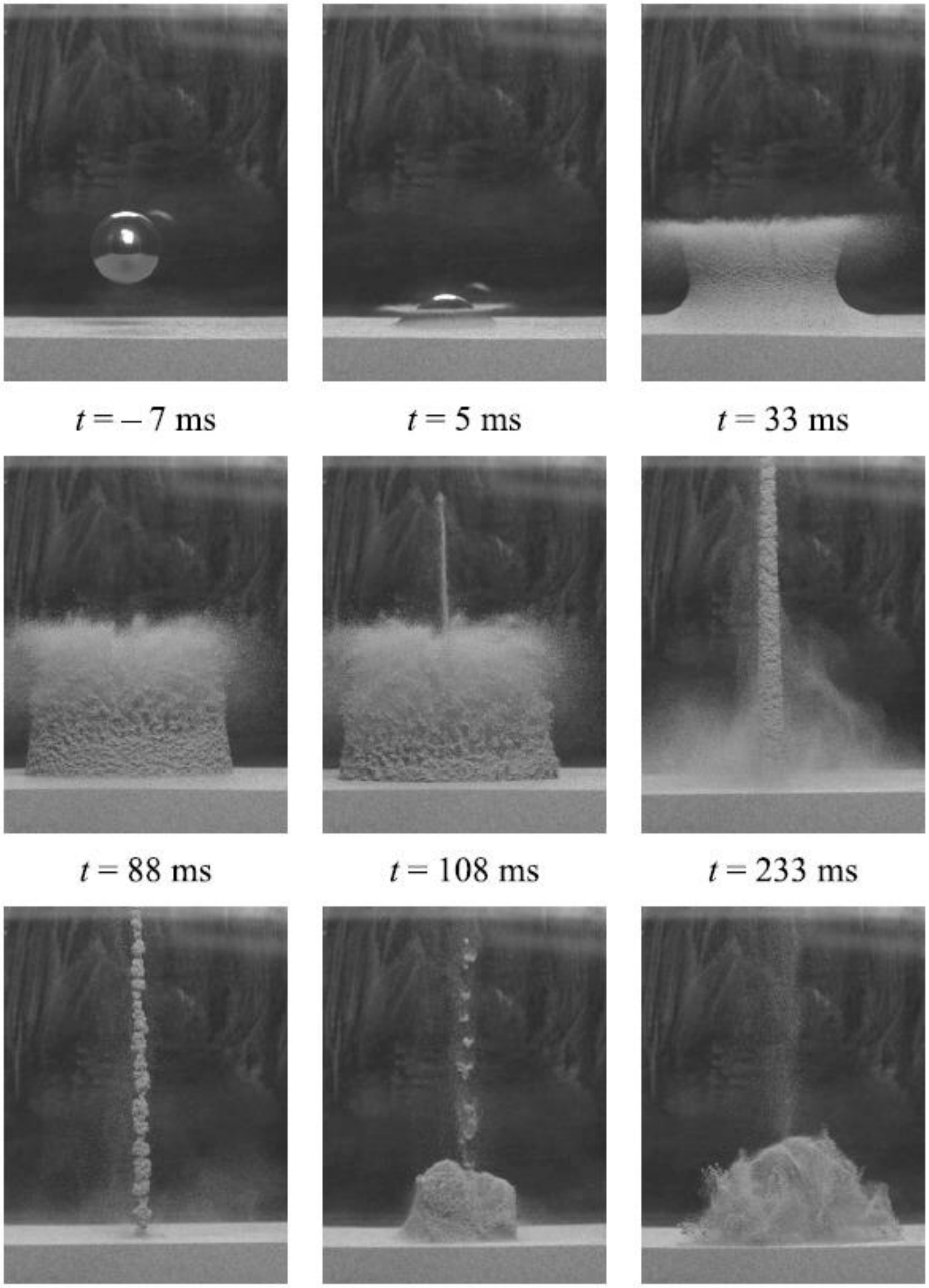
It is typically easier to identify through direct measurement what properties a specific media has, rather than to theoretically explain the properties of every different media in nature. As a result of variation between the properties of the same media at different conditions, such as moisture content and void fraction, there is currently little that can be done for predicting the penetration of any given projectile in a particular media so steps are taken to avoid classification of projectile/target-material combination and classification of the media alone is promoted. One approach used for determining the elastoplastic properties of granular media is based on the analytic approach and represents the dynamic resistance to shear in the form of a linear fractional function, which depends on a set of parameters having a clear physical meaning of adhesion, the angle of internal friction, and the ultimate resistance to shear [18].

2.3.1.1 Moisture Content

One important finding in [19], is that a projectile's penetration into saturated soil is greater than into the same dry sample. It is also demonstrated that shock waves dampen quicker in wet sand than in dry even though the projectile may travel further [19]. Several mechanisms are responsible for the decrease in penetration depth in dry sand, but slower shock dampening (increased radius of shock wave propagation) and higher friction are thought to be the dominant mechanisms. It is said that the penetration is somewhat lubricated by the presence of water in the media [20]. These findings are also confirmed by [12] as well.

2.3.1.2 Loose vs. Compacted

There have been studies on the reaction of soft sand and the effects caused by projectile penetration. One interesting method for testing is introduced by [6] in which the media is carefully de-compacted by bubbling gas through it. This allows the dry granular matter (sand) of grain size 40 μm to have a fluffy response to the projectile; making the granular material more susceptible to displacement by air pressure. One observed phenomenon is the void collapse that occurs behind the projectile and the pressure-spike induced granular jet that follows (see Figure 6 below).



$t = -7$ ms $t = 5$ ms $t = 33$ ms

$t = 88$ ms $t = 108$ ms $t = 233$ ms

$t = 358$ ms $t = 503$ ms $t = 583$ ms

Figure 6 Projectile Penetration into Soft Sand [6]

The images in Figure 6 were taken with a high-speed camera, and the projectile shown is a steel ball of radius 1.25 cm dropped from a height of up to 1.5 m, and the depth of the sand is approximately 25-40 cm. This is a classic example of the effect on soft sand, but clearly the same reaction would not occur upon impact with compacted sand. There would be a distinct difference between the media shown and the same media compacted [6, 21].

2.3.1.3 Container Effects

For the current study it is important to understand the effects the container has on a target sample's ability to expand and move when a projectile penetrates. It has been mentioned that the penetration of loosely piled sand is greater than that of sand in a bag by a factor of 4/3 to 2, and the reasoning behind it is somewhat intuitive. When a projectile enters the sand it first causes a splash. If there is a bag around the sand, this initial splash is attenuated, but as the bullet penetrates, the boundary conditions on the sample bag are held within close proximity of the original positioning, with the ability to expand slightly. After this initial expansion, the sand is forced back inward by the constraining bag. This causes increased pressure on the projectile, as the sand, that would have been pushed away, reverberates some of its energy back to the bullet slowing it more quickly. Another way effects of the container can be considered is through the density effects and similarly, the effective density. Effective density is used to describe the density of granular matter which is also inversely proportional to the void fraction. The density can play a significant role in determining penetration depth, but is relatively unchanged by compression unless the sides of the sample are contained during loading [22].

2.3.1.4 Microstructure of Target Sand

There is much interest in understanding the mechanisms that cause a granular bed to orient itself especially from the granular materials industry. The common problem confronted is the granules' ability to flow as a liquid under certain conditions and not under others [22]. This can become detrimental to a sorting facility if not handled properly. Currently the beds of grains are coerced to move by sinusoidal oscillations of the holding vessel. This method develops a certain microstructure or packing order in the vessel and is of interest to not only the industry, but to the physics community as a whole because of the implications it has with respect to increasing density and solids fraction of various granular materials [23].

2.3.1.5 Frozen Soil

There have been tests on frozen soil to see if the penetration equations given by [12] (Equation 1) and also Ross and Hanagud, can provide accurate predictions for penetration depth into frozen soil. It is indicated that upon selection of the proper material constants, both equations result in fair predictions for impact velocities below 600 m/s [16].

2.3.2 Influence of Size/Shape

There are currently scaling issues being confronted by researchers in terminal sand ballistics. In order to successfully model impacts with granular materials, the grains of the media have to be idealized as perfect inelastic spheres. They must also be made larger, with respect to the projectile, than are normally confronted in practice. This is due to the overall number of grains that can be handled by current computing abilities. This makes translation to real systems slightly harder because the virtual grains are so dissimilar to the real grains. It is stated in [2] that “the dynamics of the projectile do not scale linearly with projectile size as several investigations have expected or tried to explain”. However, with proper inspection of scaling effects, it can be shown that there is a connection between virtual and real systems and possibly an ability to extrapolate the results for other systems [16, and 22].

2.3.3 Shock Wave Propagation

Shock wave propagation is an important facet of impact engineering because of the energy displacement that occurs through this mechanism. The shock waves in saturated sandy soil can be computed using Mie-Grüneisen provided the Mie-Grüneisen constants and the dimensional speed of sound can be computed for the target medium. As previously stated, the shock waves dampen quicker in wet sand than in dry [19].

2.3.4 Ideal vs. Non-Ideal Impact

Perfectly perpendicular collisions between projectiles and targets are ideal for maximum penetration, but are not always present in practice. Studies have been performed on various impact orientations to determine the response characteristics of both the target and the projectile [24, and 25]. Since the adverse penetration effects, such as ricochet, are minimal when the angle of approach is close to 90°, the classification of impact for this study is taken to be ideal.

2.3.5 Buckling and Phase Transition Effects

The effects of penetration usually entail high pressures and temperatures at the leading edge. For this reason it is important to discuss the parameters leading to buckling and phase transition. In some cases, such as in [5] the penetrator can be deformed and even melted and re-deposited on the shaft of the projectile.

For buckling, Euler's Buckling formula (Equation 4) aids in identifying the loading necessary, and determines when the projectile will deform under the dynamic loading conditions that occur during penetration [19]. [5, and 20]

$$EI\frac{d^2}{dz^2}+(aV_0^2+b)y=0; y(0)=y(L)=0 \tag{4}$$

It is necessary to obtain accurate transient-displacement information in order to determine the acceleration of the projectile which will cause buckling to occur, but in the case of fine, saturated sand and projectile velocities at or below 700 m/s, the projectile typically suffers little deformation. The effects of wear can be seen on the projectile's surface after impact.

2.3.6 Granular Jets

An interesting topic of granular penetration is the phenomenon of granular jet formation. As seen in Figure 6, the granular jet that shoots from the surface, just microseconds after impact, is very similar to one formed by impact with water (see Figures 6 and 7) [26].

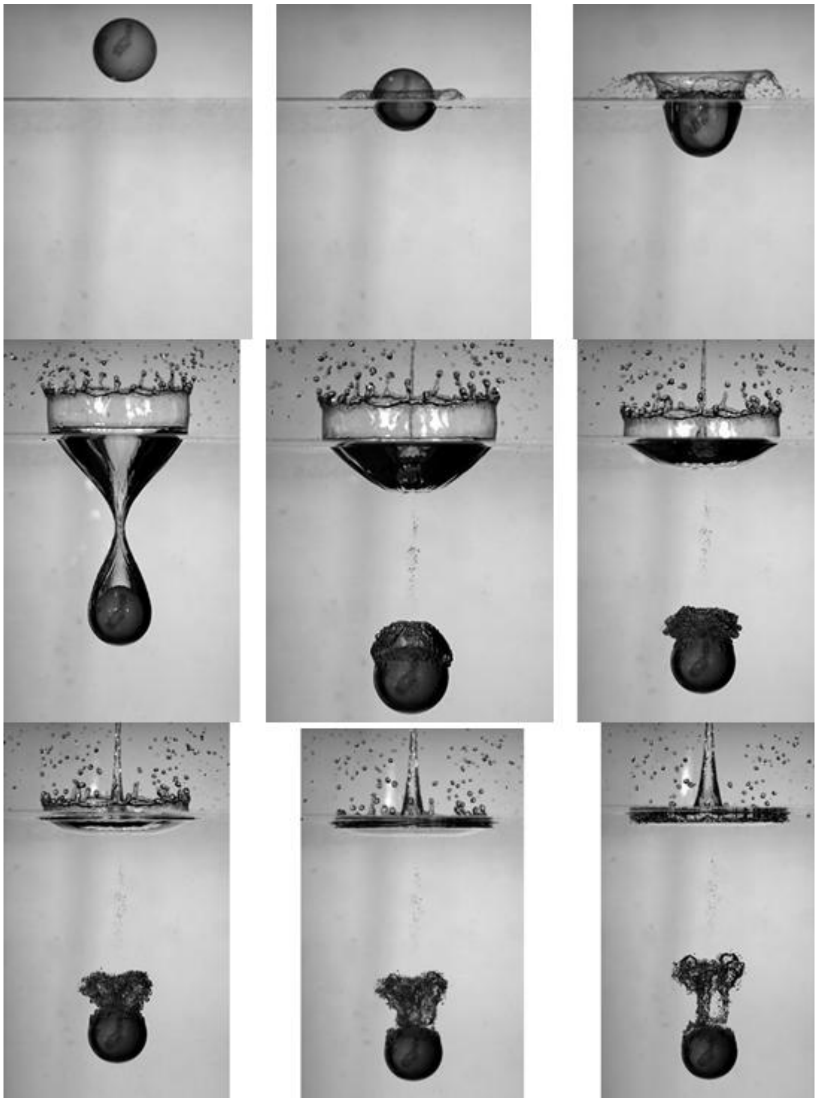


Figure 7 Projectile Impact with Water [27]

Here, the water gives evidence to the mechanisms that cause jet formation. The solid sphere impacting the surface causes an ejecta sheet and transient axisymmetric crater. It can be noticed that there is a void following the projectile that closes, causing the pressure to spike under the surface, resulting in a jet of water projecting through the air in the opposite direction of penetration. This phenomenon is known as void collapse. The same effect occurs in granular media and has certain characteristics that pertain to this study. For instance, the Reynolds number is said to reduce to a geometric factor which is constant for each grain size, and with an increase in grain diameter by a factor of 10 (reduce Re by 100 in formulation) for frictionless flow predicts a 10-fold reduction in the height of the jet, but experimentation suggests a 100-fold reduction. This has implications on the fluid-like nature of sand and gives insight to one of the many possible effects of altering grain-size.

2.3.7 Impact Cratering

Cratering is under investigation by astrophysicists searching for a better understanding of how crater formation is linked to projectile size and speed. It is essential such that educated assumptions can be made about past and future impacts of celestial bodies. In the current study it is important to understand the mechanisms that cause crater formation and the mechanisms that prevent it from occurring in containment vessels such as sandbags. In sandbags crater formation from a horizontal impact is quickly erased by small avalanches or cave-ins, and does not directly determine penetration depth, but it does have importance when discussing the numerous effects of projectile penetration in granular materials.

Impact cratering has two distinct regimes of formation defined by the opening dynamics and partial closing. It is noted that the opening dynamics can be modeled by an exponential saturation while the partial closing can be understood through the dynamics of avalanching. The disturbance in the media is also said to have a well-defined propagation velocity [2, and 28].

2.3.8 Applicability of Rigid Body Dynamics

One question raised about the dynamics of impact between a “hard” projectile and a granular medium is in regards to the ability of the grains to act as rigid bodies. It is clear that the particles themselves do, for the most part respond as rigid bodies, but as noticed by [12], there are other, non-rigid-body, collisions in the granular media that are evidenced by crushed and broken grains. This facet alone breaks granular impacts from what would be handled through the theories of rigid body dynamics. Another is the vibrational motion occurring within the medium, which according to [30] is not corrected by the coefficient of restitution even when friction is factored in [4].

2.4 Analytical Models

Through the history of sand ballistics there have been many attempts to describe quantitatively the response of a granular medium. This is typically done by integrating the acceleration equation of the projectile to find the transient displacement as a function of impact velocity, which can lead to extraneous data points such as when velocity approaches zero. Also, the analytical models cannot take all variables into account that are found in impacts with granular materials such as moisture content, grain size variation, grain shape variation, etc. [1, 5, 28, and 31]. Nearly all models published have empirically derived constants that entailed experimental observations on the media. Studies performed on other materials have determined the pressure needed to accelerate the projectile from its initial velocity to stop in the given time. This method does not take into account the mechanisms involved, it merely uses the average value for pressure resisting penetration (P) equated with the initial kinetic energy (see Equation 5) [32].

$$PAd = \frac{1}{2}mv^2 \tag{5}$$

Another factor that differs from source to source is the effect of gravity. For the most simplified studies pitting a steel ball dropped from a specific height versus a bed of granules under the acceleration of gravity, gravity must be factored in, but with regard to this study, there is a negligible effect of gravity because the projectile travels horizontally through the medium [6]. Not only does this eliminate the gravity term in the equation, but also the "hydrostatic" pressure effects of penetrating deeper into the media. These are present for the case of horizontal penetration path, but are relatively constant as depth stays constant.

2.4.1 Drag and Force on Projectile Penetrating Target

As stated previously there have been efforts to determine forces on a projectile by estimating the average pressure created upon impact [32], and other studies that have tried to explain the mechanisms which cause the pressure and forces, but currently there is no cohesive theory that describes penetration into granular media [5, and 33]. In [22] (2008), the author states: "however, because the physics of such events must account for both fluid- and solid-like behavior during impact, the understanding remains limited. No comprehensive continuum theory exists for even the relatively low impact velocity of a rock dropped into beach sand from an outreached hand".

2.4.2 Structure of Granular Systems

Another aspect of granular penetration science is in the understanding of how the granulate is arranged. It is impossible to quantify the variation of structure in mathematical terms outside of the statistical realm. The individual grains of the sand are inherently individual in shape, and size which prevents the analytical solution for the structure of the bed. That can be optimized by very specific sorting and regulation of shape of grains, but it takes from the practicality of real world application. If the grains must be meticulously selected so the model will produce good results, then there is still disconnect between the model and the real system reaction; proving the analytical approach still only provides estimates, which can also be achieved through Equation 1 provided the constants are chosen appropriately (a method that can very easily give upper and lower bounds for penetration depth).

2.5 Simulation Capabilities

Beyond the experimental and analytical methods, is the simulation method. As stated previously, currently the number of grains that can be modeled is on the order of 10^6. The number of grains in a cubic foot of sand is on the order of 10^9. This does not allow for the simulation of even a standard round penetrating beach sand. There are studies performed with quasi 2-D simulation and experimentation. These simulations involve a cylinder dropped into a container with either smaller cylinders or spherical grains. In some cases the spherical grains are limited to a depth of eight grains such that the overall number is kept near 10^6 [6]. Other simulations are used to determine ballistic characteristics of composite materials [32]. This type of analysis is beneficial because, once the model accurately predicts effects for a given sample, and is compared with test data, the model can be adjusted to test a multitude of combinations without excessive experimentation.

2.5.1 Particle Algorithms

Particle algorithms are used to simulate various materials from solid homogeneous materials such as steel and aluminum to granular matter such as sand. The capabilities of this modeling technique are still limited by the number of particles used. In [7] a generalized particle algorithm (GPA) for high velocity impacts and other dynamics problems is presented. Topics are also discussed such as nodal connectivity (fixed and variable), which is determined by the level of distortion such that computation time is minimized without hindering results. Variable nodal connectivity allows for nodes to share different neighbors throughout the computation, while fixed nodal connectivity can be used through small deformations to facilitate faster computation time. Artificial viscosity is discussed in two forms: nodal viscosity and bond viscosity. It is stated that nodal viscosity is equivalent to that used in finite element and finite difference methods. The "mushrooming" effect observed when cylindrical projectiles strike a hard surface is discussed and modeled using this technique as shown in Figure 8 [7].

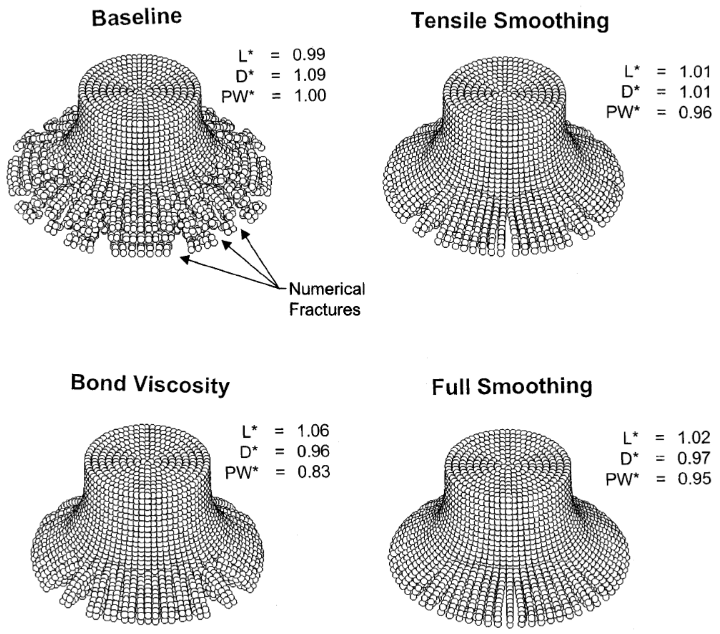


Figure 8 Simulation of a Cylinder Impacting a Hard Surface [7]

The nodes are easily seen along with possible fracture sites. This type of model can be used to represent the projectile (as shown) or the granular media. The difference lies in the nodes ability to move freely when the nodal connectivity is negated. Here it becomes imperative to accurately depict the boundary conditions.

2.5.2 Finite Element Analysis

Finite element analysis is not amenable to this study aside from the ability to model the projectile. It would not be reasonable to model every grain as an individual elements for two reasons: 1) the shape of the elements would not represent the shape of the grains without having either spherical elements or multiple elements per grain, and 2) the boundary conditions between nodes would require extra computations as elements move throughout the simulation which would exponentially increase computation time [23, and 34].

2.6 Bullet Trap Design

There has been much consideration for the design of bullet traps at firing ranges because of the need for tough containment. A bullet trap can capture tens of thousands of rounds in a typical lifespan. The basic idea for bullet trap design is to capture the projectiles without endangering the shooter. Traps come in many forms (as shown in Figures 9-12), and vary in size and capacity. The traps shown vary in capacity from 10,000 (Figure 12) to 100,000 rounds (Figure 10). It is important to note that all traps shown utilize either tires or granulated tire material which is of low cost and is readily available [35, 36, 37, and 38].

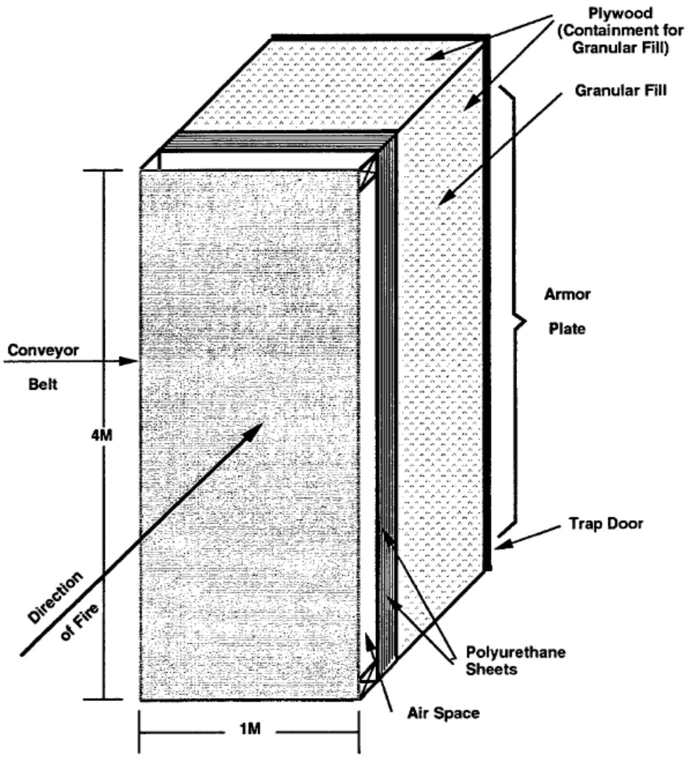


Figure 9 Granular Fill Bullet Trap [37]

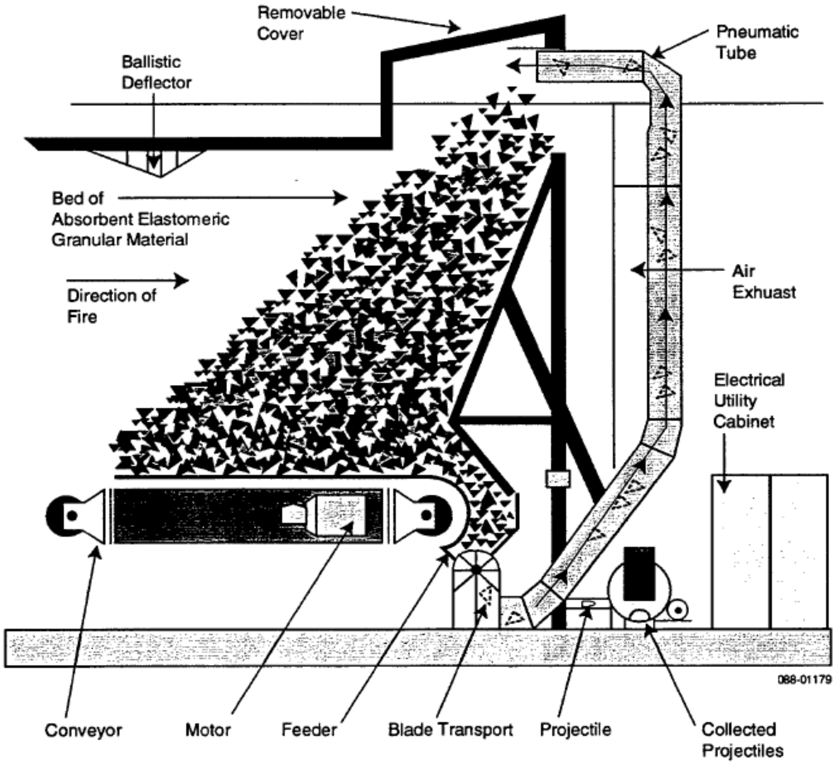


Figure 10 Re-Circulating Crumb Rubber Trap [37]

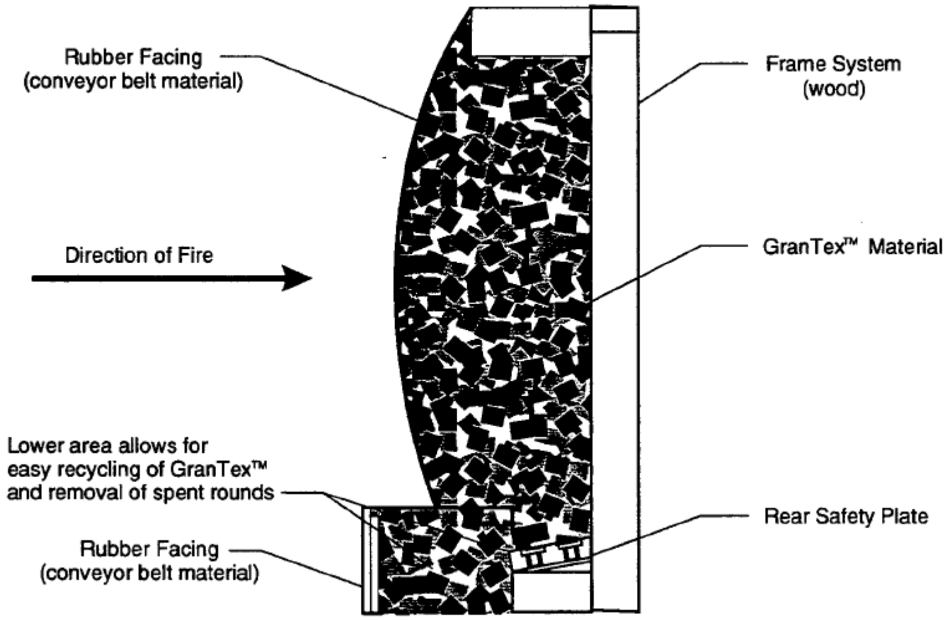


Figure 11 Stationary Crumb Rubber Trap [37]

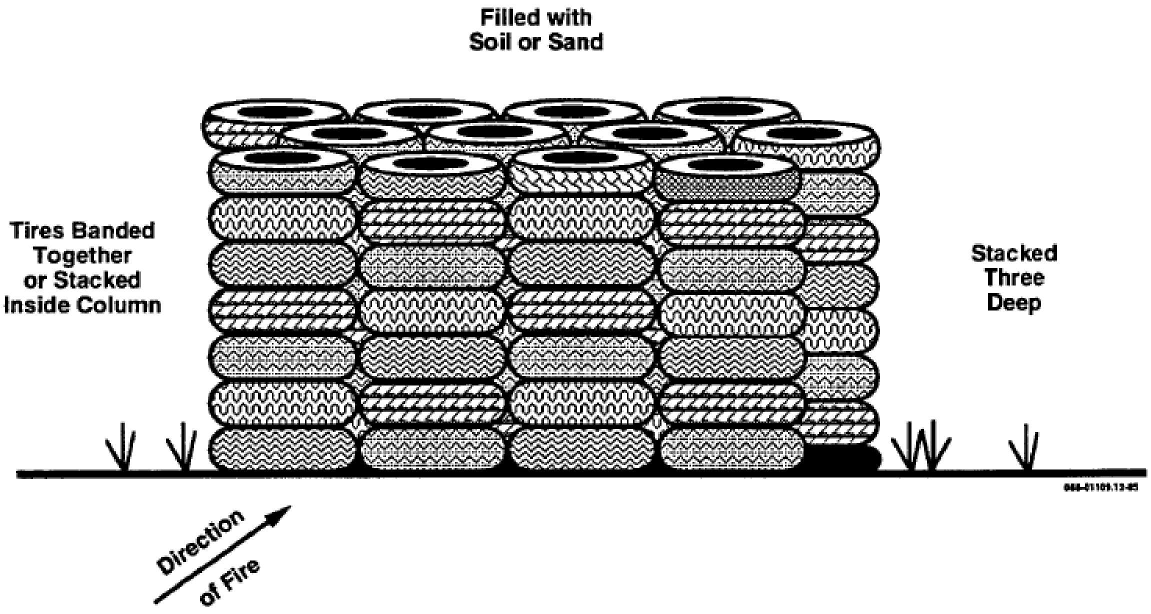


Figure 12 Earth-Filled Tire Trap [37]

2.6.1 Lead Contamination

Recently there has been much concern over the heavy metals leaching from firing ranges. It is stated that about 4% of the 2 million tons of lead produced in the 1990's (180 million pounds) was made into bullets and much of this makes it into the environment at firing ranges. As a result, measures are being taken in new bullet trap design to contain spent rounds for recycling. Sand has been recently studied a possible low-maintenance alternative to higher-priced traps (see Figure 13 below). [3, and 39]

Agents can be added to the sand to capture heavy metals before they leach from the firing range with as great as 90% effectiveness.

Figure 13 Passive Reactive Sand Berm [3]

Chapter 3: Experimental Setup

The present study was designed to assist the military by determining the optimum grain size of sand or crumb rubber to use in sandbagged fortifications. To this end, military style sandbags were used, and filled and stacked to military specifications. Bullet caliber and manufacture similar to that used by the Taliban in Afghanistan was used [40].

There are many variables in determining ballistic penetration in granular systems from the shape and size of the penetrator to the grain size of the matter. Many characteristics are taken to be relatively constant for the purposes of this study such as the grain roundness, compaction of the bed, and the angle of approach for the projectile. The reason is to clearly define a reasonable scope without sacrificing the realistic nature of the scenario.

3.1 Materials

Materials for this study were purchased from local wholesale producers of silica sand and crumb rubber. The need for multiple sizes of the same sand proved difficult, but eventually lead to Florida Silica Sand Company with a location in Plant City, Florida, who produces four grades of silica sand and many other granular products and stones. The crumb rubber was purchased directly from an industrial recycler of used tires named Global Tire Recycling located in Wildwood, Florida. The granulate materials can be seen in Figure 14 (below) compared to the size of the 7.62x39 round. The sandbags used to hold the granulate materials were purchased from esandbags.com.

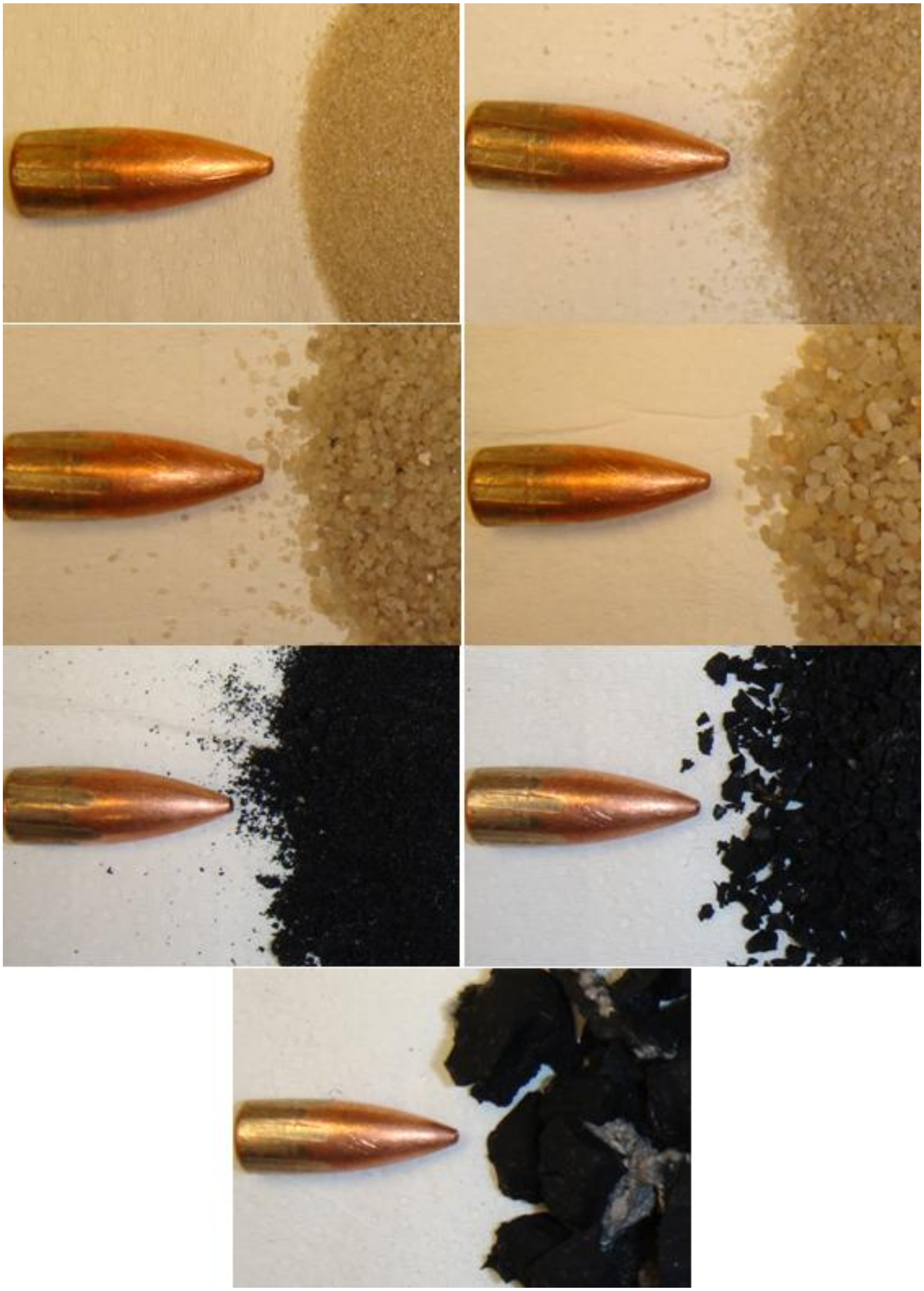


Figure 14 Granulate Materials with the 7.62x39 Projectile

3.1.1 Sand

The sand, as stated before, is silica sand which has been screened through different sieves of varying sizes. A statistical analysis has been performed on the test sand to determine the mean major dimension of each grade in order to compare the findings with the respective mesh sizes given by the producer. The mean major dimension sizes (on a 97% confidence interval), are: 0.355 ± 0.039, 0.813 ± 0.045, 1.178 ± 0.104, and 2.19 ± 0.21 mm for the 60/80, 30/65, 20/30 and 6/20 meshes respectively. The mesh openings are given as 0.177, 0.250, 0.210, 0.595, 0.841 and 3.36 mm square, for the 80, 60, 65, 30, 20 and 6 meshes respectively [41]. As previously stated, granulates are categorized by their ability to pass through one screen and be retained by another. Samples are shown below in Figures 15-18. The effective density was measured to be approximately 1421, 1520, 1630, and 1658 [kg/m^3] for 60/80, 30/65, 20/30, and 6/20 mesh sands respectively.

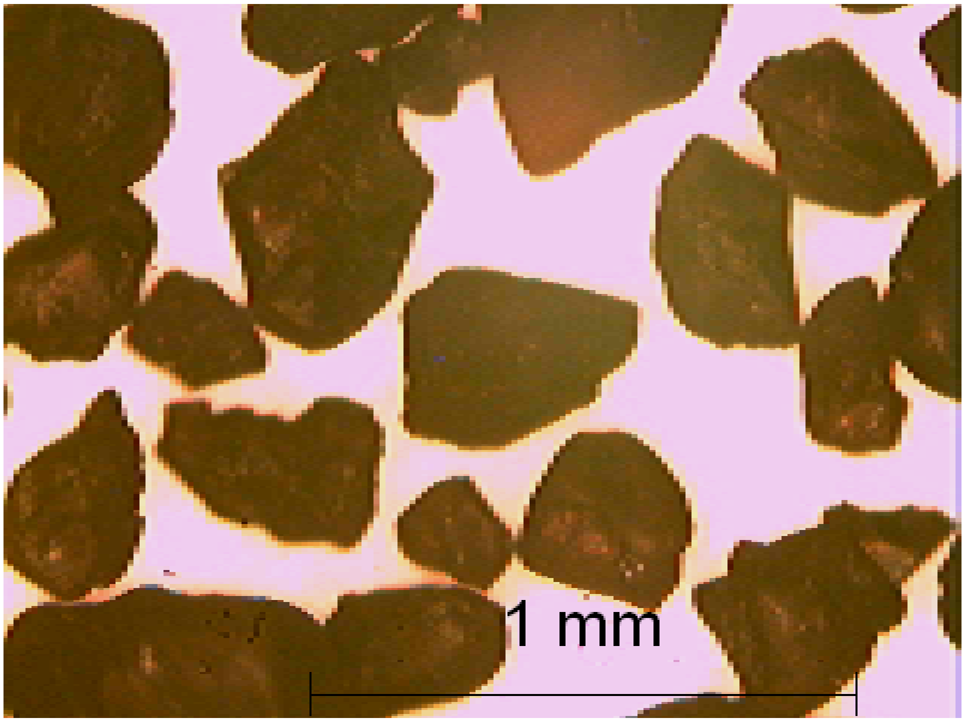


Figure 15 Test Sample of 60/80-Mesh Sand 5x Magnification

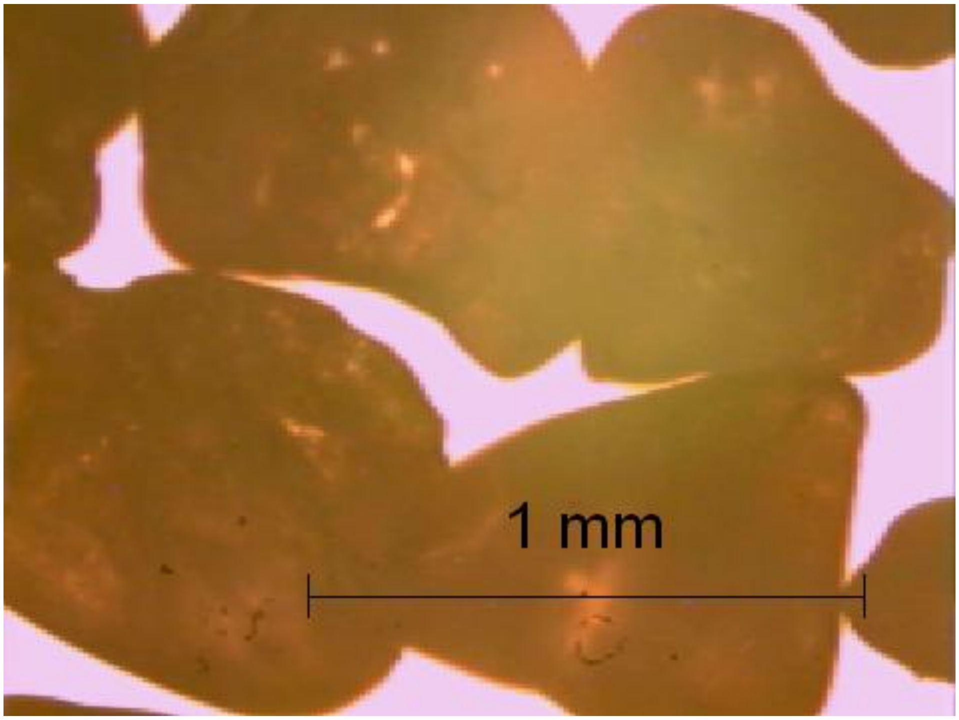


Figure 16 Test Sample of 30/65-Mesh Sand 5x Magnification

Figure 17 Test Sample of 20/30-Mesh Sand 5x Magnification

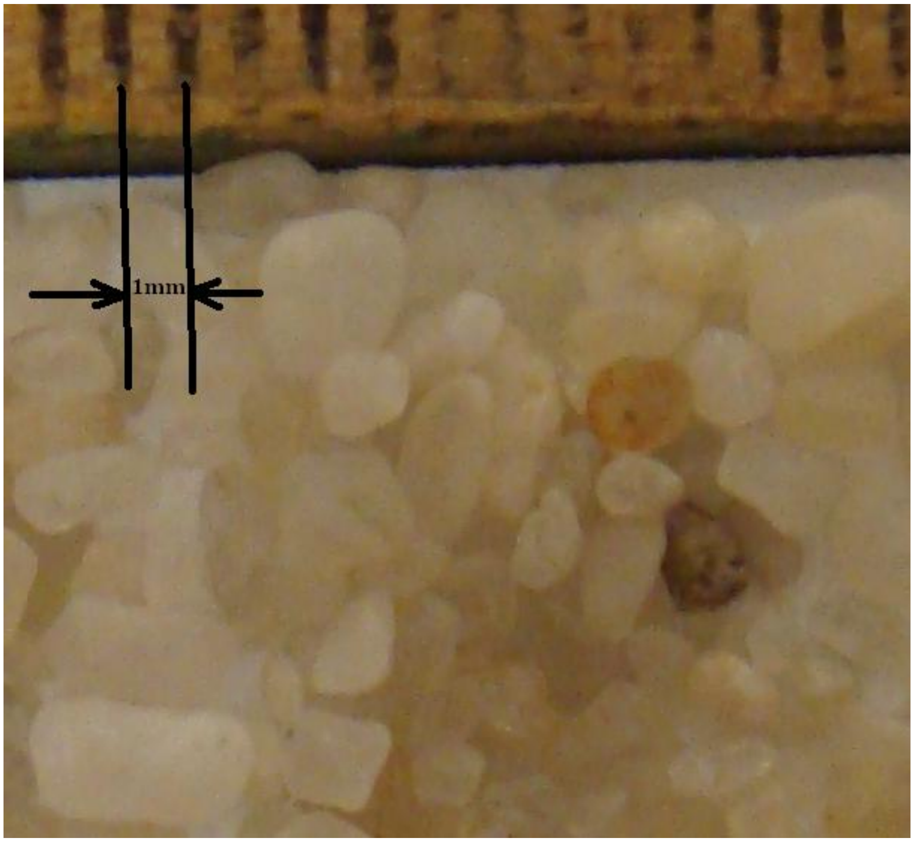


Figure 18 Test Sample of 6/20-Mesh Sand

3.1.2 Rubber

The rubber is made from recycled tires. The producer gives what appears to be the average size. A statistical analysis has been performed on the test rubber to determine the mean major dimension of each grade in order to compare the findings with the respective sizes given by the producer. The mean major dimension sizes from the samples taken (on a 97% confidence interval), are: 0.305 ± 0.070, 2.58 ± 0.30, and 14.90 ± 1.38 mm for the 40 and 14/30 meshes, and 3/8 inch sizes respectively. The mesh openings are given as 0.420, 0.595, and 1.19 mm for the 40, 30, and 14 meshes respectively [41]. As previously stated, a granulate is categorized by its ability to pass through one screen and get retained by another except in the case of the 40 mesh rubber that has no lower bound. Samples are shown below in Figures 19-21. The effective density was measured to be approximately 398, 478, and 409 [kg/m^3] for 40 mesh, 13/40 mesh, and 3/8 inch rubbers respectively.

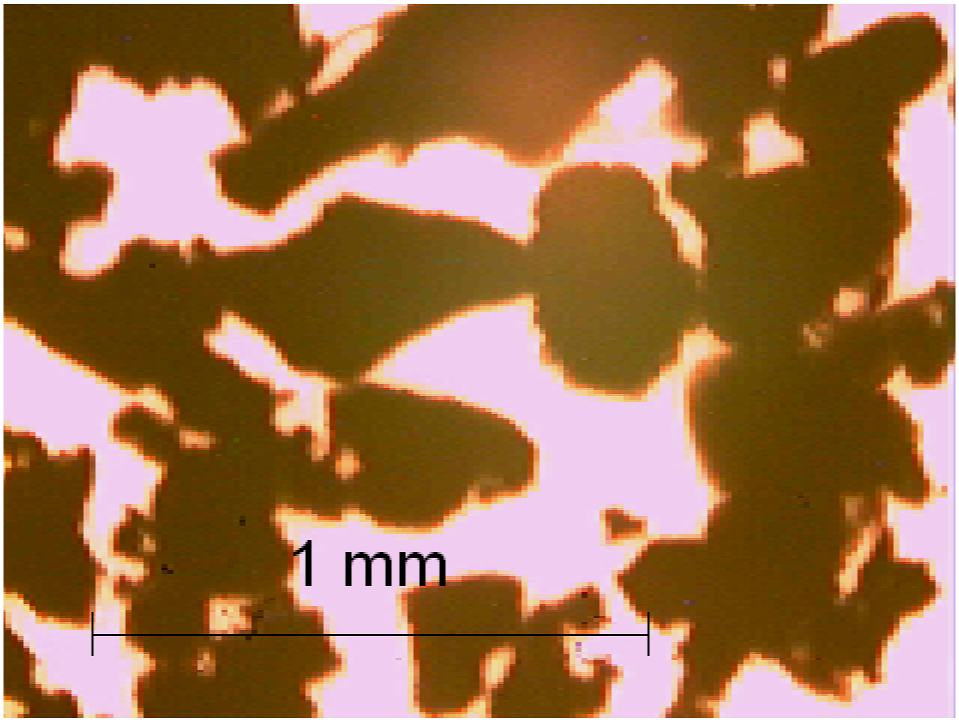


Figure 19 Test Sample of 40 Mesh Rubber 5x Magnification

Figure 20 Test Sample of 16/35 Mesh Rubber

Figure 21 Test Sample of 3/8 Inch Rubber

Table 1 (below) shows all of the various media and the measured material properties.

Table 1 Material Properties

Granulate	Mean Major Dimension [mm]	97% CI on Mean	Effective Density [kg/m3]	Sieve Sizes [mm]
Sand				
60/80 Mesh	0.355	±0.039	1658	0.177-0.250
30/65 Mesh	0.813	±0.045	1630	0.210-0.595
20/30 Mesh	1.178	±0.104	1520	0.595-0.841
6/20 Mesh	2.19	±0.21	1421	0.841-3.36
Rubber				
40 Mesh	0.305	±0.070	398	0-0.420
14/30 Mesh	2.58	±0.30	478	0.595-1.19
3/8 Inch	14.90	±1.38	409	9.525

3.1.3 Projectiles

In order to maintain the realistic nature of the experiments the projectiles used are some of the most widely available and common types of ammunition on the market. The rounds tested are the 123 grain full metal jacket (FMJ) Silver Bear 7.62x39, and the 115 grain FMJ Brown Bear 9mm (see Figure 22). These rounds were used because as stated in [40], Taliban forces were found dead after a firefight with 7.62x39 ammunition in their AK47's which was of Russian origin. Therefore, the ammunition chosen for testing was Russian. Also, the 9mm is one of the world's most widely used rounds for handguns, and therefore was chosen to show the effects of a much slower projectile. The ammunition was purchased through www.cheaperthandirt.com, an online dealer.

Figure 22 Ammunition Used During Testing

3.1.4 Firearms

The firearms used during testing are the AR-15 assault rifle, and the P226 9mm by Rock River Arms and Sig Sauer respectively. The AR-15 (which normally fires the .223 caliber) has a conversion kit that chambers the rifle to shoot the 7.62x39 round normally found in the AK-47 and SKS assault rifles along with several others (see Figures 23 and 24 below).

Figure 23 AR 15 Assault Rifle

Figure 24 P226 9mm

3.1.5 Sandbags

The sandbags used are 14x26" in size and made from polypropylene mesh. The bags are 1600 hour UV rated standard military-issue sandbags. The sandbags were found through amazon.com, and purchased from www.esandbags.com, an online dealer (See Figure 25).

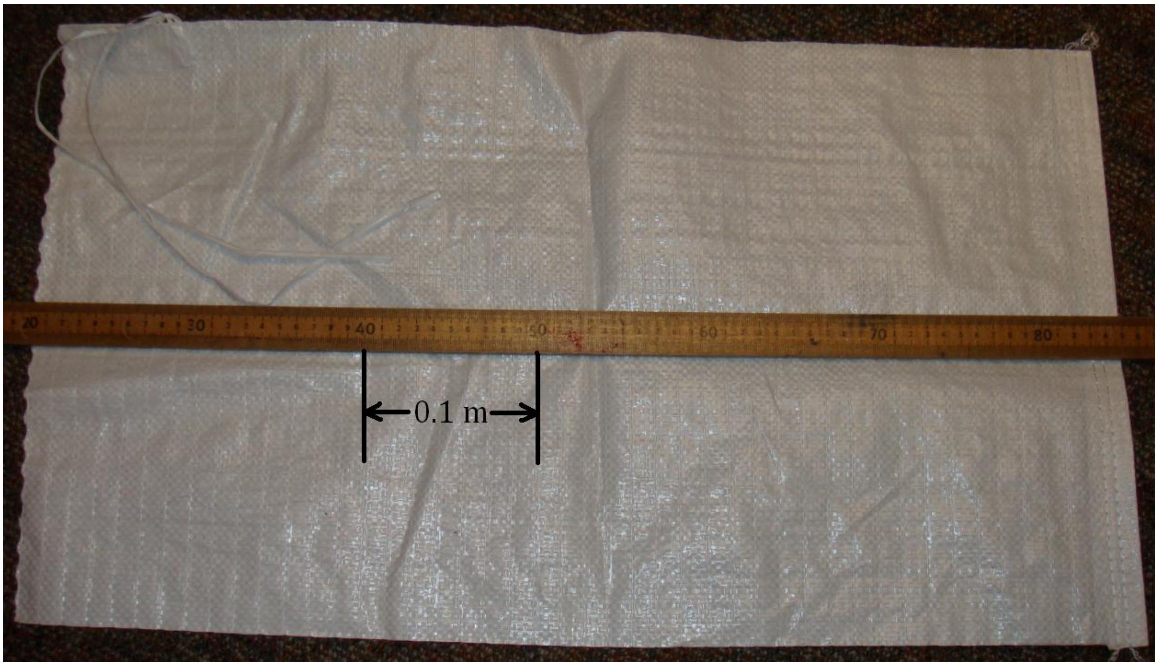


Figure 25 Sandbags Used in Testing

3.2 Method

In order to study the effects of varying grain size, it is important to maintain consistency from test to test. The granular matter used was purchased locally and bagged on-site in standard military-issue sandbags. The sandbags are used to contain the granular matter in a real-world battlefield type situation. There are some parameters that are uncontrollable, such as moisture content, but this was measured.

3.2.1 Sandbag Barrier

The sandbags were stacked and filled in accordance with the US Army Corps of Engineers handbook [42]. Sandbags were filled with target material and placed in a pyramidal stacking order as shown in Figures 26, 27 and 28. This form of barrier is easily constructed and is tough enough to handle multiple rounds without failure. The pyramid starts with a layer of five bags by five bags, then a layer four bags by four bags, then three by three, two by two, and topped by a single bag. The stack was positioned such that the long side of the bag faced the oncoming projectiles.

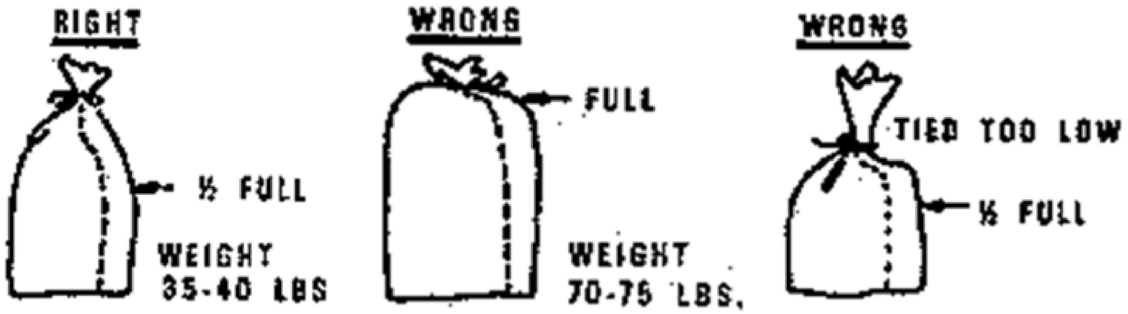


Figure 26 How Properly to Fill Sandbags [42]

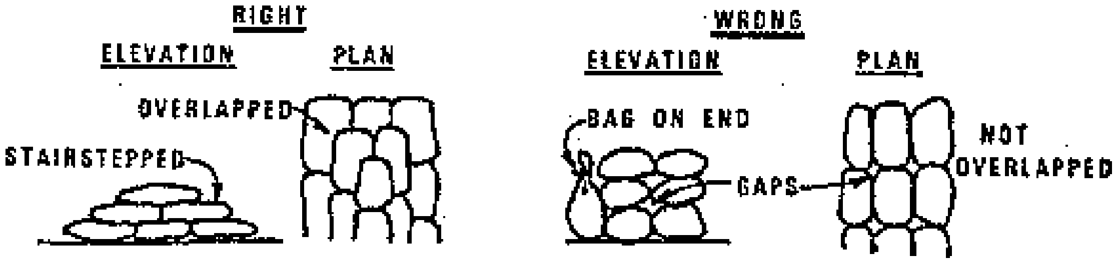


Figure 27 Proper Assembly of a Sandbag Barrier [42]

Figure 28 Assembly of the Sandbag Barrier

As mentioned before, there are differences in the reaction of contained sand and loose sand. There is also a difference between interior bags and the top row which is unconstrained on the top and sides; for this reason, the target bag is an interior bag, not on the top and not on the bottom. The target bag was positioned in the center of the stack, or, the third layer, center bag of the three exposed that face the oncoming projectiles. For the purposes of maintaining consistency, the target bag is replaced after each shot. This required un-stacking the top bag, the two by two layer and removing the target bag (or bags) from the third layer.

3.2.2 Positioning

For the positioning of the barrier with respect to the firing platform, there must be enough room between the two to facilitate use of the chronograph or velocity measurement apparatus. For the use of the rifle and the 7.62x39 round, the shooting platform was positioned about 40 ft up-range from the sandbagged redoubt with the chronograph placed about 10 ft in front of the barrier, as shown in Figure 29.

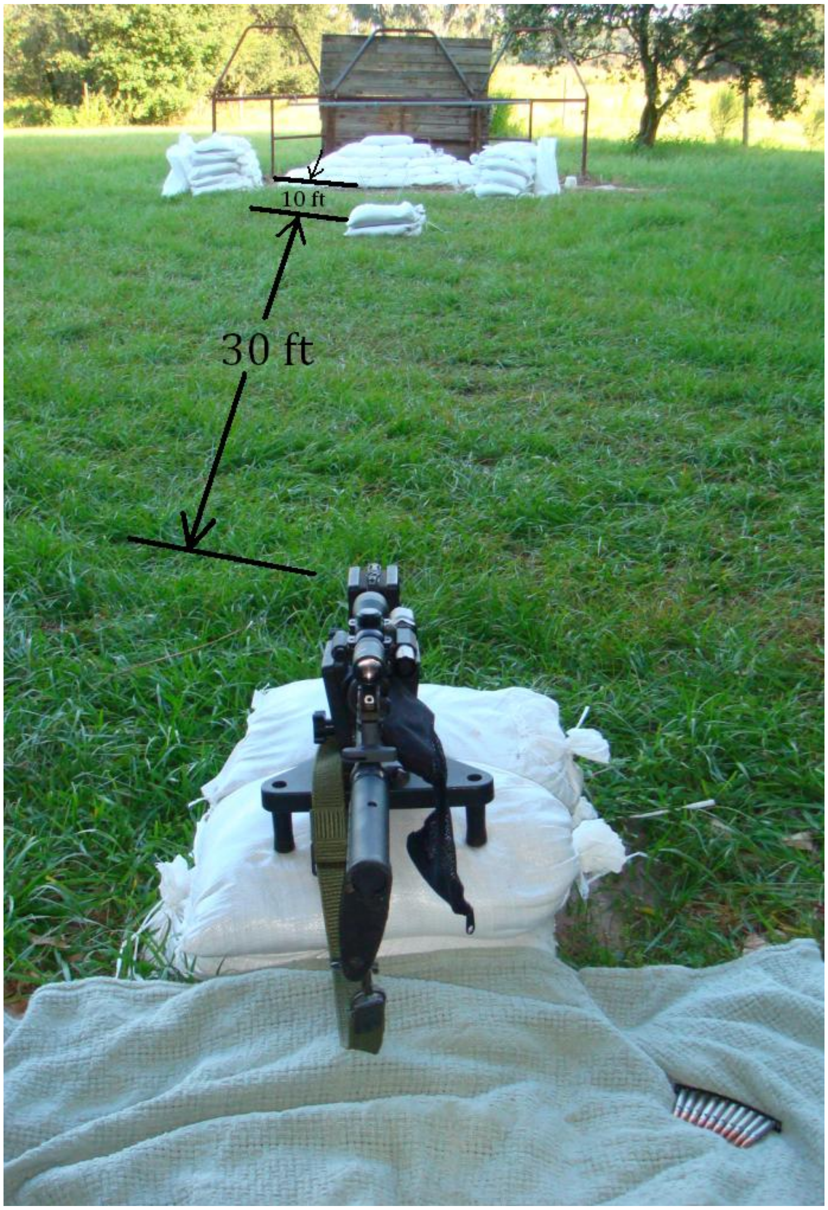


Figure 29 Setup for 7.62x39 Testing

For the use of the pistol, the shooting platform was positioned about 9 ft from the barrier with the chronograph in the center as shown in Figure 30. The target layer of sandbags was aligned with the line-of-shot, such that the tops and bottoms of the bags were not penetrated by the most deeply penetrating rounds.

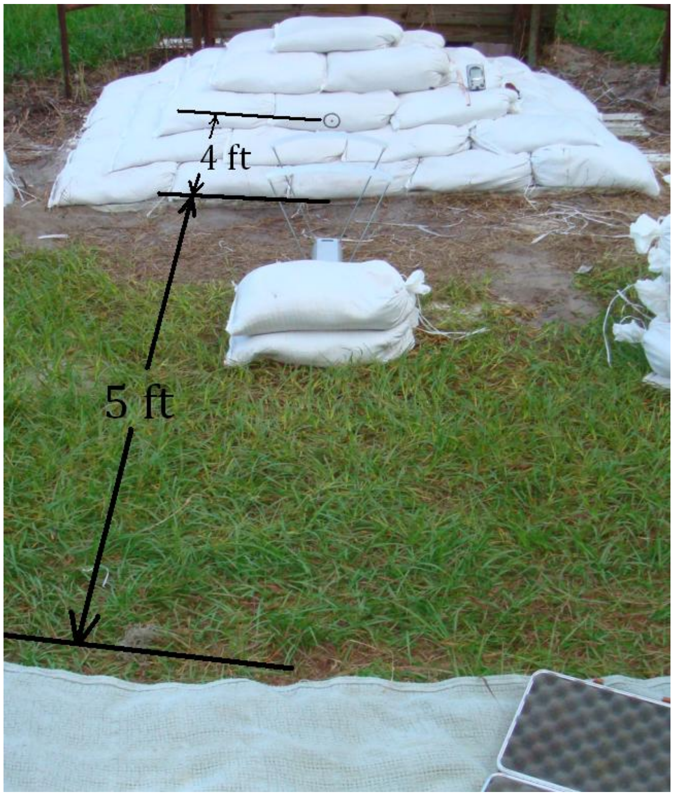


Figure 30 Setup for 9mm Testing

3.2.3 Measurements

Well taken measurements are the most important aspect of any testing. Therefore, the measurements were taken with extreme care and consistency. There were several measurements taken: average grain size, weight of full sandbag, moisture content of the granular media, projectile weight, projectile velocity, and penetration depth.

3.2.3.1 Grain Size

Grain size was measured by the Leitz Optical Microscope and software at the Nanotechnology Education and Research Center at the University of South Florida Tampa Campus, and by a Mitutoyo micrometer for the larger grain sizes. The average size of grains is found through a statistical analysis of the largest length measured from up to 100 different grains (see Appendix B). The sample was taken from each of four sizes of sand and from the three sizes of crumb rubber.

3.2.3.2 Full Sandbag Weight

The weight of each filled sandbag was measured by scale and filled to the same weight of 40 and 13.5 pounds for the sand and rubber respectively. As shown in Figure 26 above, 40 lb is the recommended weight to fill sandbags with sand [42]. The density was measured to be approximately 1421, 1520, 1630, and 1658 [kg/m^3] for 60/80 mesh, 30/65 mesh, 20/30 mesh, and 6/20 mesh sand respectively and approximately 409, 478, 398 [kg/m^3] for 40 mesh, 14/30 mesh, and 3/8 inch crumb rubber respectively. Although the density varies slightly, the sandbags were filled to the same weight, not volume. For the rubber, a bag was initially filled until the volume approximately matched that of the sand, and then measured to be 13.5 pounds.

3.2.3.3 Moisture Content

Moisture content was measured by a standard analog soil moisture meter (see Figure 31 below). The meter has a scale from zero to ten. When the dry sand is measured there is no change in the needle position from its position when exposed to air, but when the meter is place in water it reads a value of ten. The measurements are relatively constant throughout testing. There is a bias in the meter that was tested by heating the sand to eliminate trace water in the sample while measuring the mass before and after with an Ohaus triple beam balance. The mass decreased less than 0.1% during this process. The moisture meter maintained a non-zero value (as shown in Appendix F). From this, it can be concluded that the moisture level during testing was approximately zero. Because the granulate materials were stored in a barn, they were subjected to slight fluctuations of air moisture with the changing Florida humidity. However, the media was kept away from rain and morning dew which allowed it to remain as dry as possible without dehumidification or air conditioning. Records of temperature and relative humidity were taken as well (as shown in Appendix A).

Figure 31 Analog Soil Moisture Meter

3.2.3.4 Projectile Mass

Projectile mass is given by the manufacturer in units of grains and confirmed by measurement with Mettler AE 260 Data Range® digital scale. Since some projectiles experience wear and deformation upon impact, and also because the projectiles cannot be removed from the cartridges and then reassembled without the proper equipment, the average mass of the ten projectiles fired into 40 mesh rubber was taken to be the average mass of the projectiles for all shots. The average mass measured was 7.999 ± 0.022 and 7.463 ± 0.023 grams (123.45 and 115.17 grains) for the 7.62x39 and 9mm respectively (see Appendix C for measurements). The manufacturers give the masses as 123 and 115 grains (7.97 and 7.45 grams) for the 7.62x39 and 9mm respectively.

3.2.3.5 Projectile Velocity

Projectile velocity is recorded by a ProChrono Digital Chronograph by Competition Electronics (see Figure 32 shown below). This chronograph is capable of measuring velocities in the range of 25 to 7,000 [ft/s] (7.6 to 2134 [m/s]) with an accuracy of 1%. It stores up to 891 velocity measurements in a non-volatile memory and can determine average velocity, standard deviation, high velocity, low velocity and extreme spread for a series of rounds. The chronograph used in these experiments utilizes light sensors that detect the passing bullet from one sensor to the next. The main limitation of this apparatus is the lighting conditions necessary to detect projectiles (no early morning or evening tests were successful). The chronograph was protected by two full sandbags placed in front of it.

Figure 32 Competition Electronics ProChrono Digital Chronograph

3.2.3.6 Penetration Depth

Penetration depth was carefully measured by tape measure from the entry point on the sandbag to the farthest point on the projectile from the entry point at its final resting position. This means that the actual penetration is measured, not the relative penetration with respect to the shooter's line-of-sight. This does not take into account any curved paths however, only straight line penetration from entry to resting point. The position of each round was first approximately located using an inductance-type metal detector, then by probing the granular matter with a fine wire to better determine the position. Finally, the layers of granulate were carefully removed by brushing and scooping it away until the projectile was exposed such that the measurement could be made. Orientation and condition of the bullet was noted along with the number of bags penetrated in the shot (see Appendix A).

3.2.4 Conducting the Tests

In order to acquire a sample of data that is large enough to base conclusions upon yet small enough to perform within a reasonable time-frame the number of tests chosen to perform is ten. With the number of tests at ten per type of round and media, having two different rounds, four different sandy media, and the weight of each sandbag at 40 pounds, the amount of sand required to be moved in and out of the stack was over 3200 pounds. This entailed moving three times that amount in order to un-stack and re-stack the barrier. Each test of sandy media required moving three bags such that the top of the target bag was exposed, finding the bullet, laying another target bag in place without causing unevenness of the target bag, and re-stacking the barrier. The time taken to find a particular round varied with its positioning inside the bag.

Each firearm was carefully handled and kept in a safe position with the safety on between all tests. The rifle was loaded with one bullet at a time without the use of a magazine. The pistol was loaded with a magazine and was directed away from the target area during the search for each bullet. The de-cocker was also utilized between each shot to ensure the gun could not be unintentionally discharged.

Chapter 4: Results

After successfully firing and recovering ten shots from each firearm into each media, the velocity, penetration depth, moisture levels and any necessary notes were recorded. The following chapter shows the product of the tests. The sand and rubber were tested against both the 7.62x39 and 9mm rounds. The penetration of each material/round combination is shown below along with comparison of the individual round and all four sands used in this experiment.

4.1 The 7.62x39 Round

The 7.62x39 round was tested for penetration in the four sizes of sand and the three sizes of rubber.

4.1.1 The 7.62x39 Round into Sand

The penetration of the 7.62x39 round in the various sandy media, as measured, is shown below in Figures 33-36. The compilation of all 7.62x39 tests into sand is shown in Figure 37. Performing a one-way Analysis of Variance (ANOVA) test on the 7.62x39 penetration into sand data gives a probability of 98.9% that penetration does depend on grain size (see Appendix D for more statistical data).

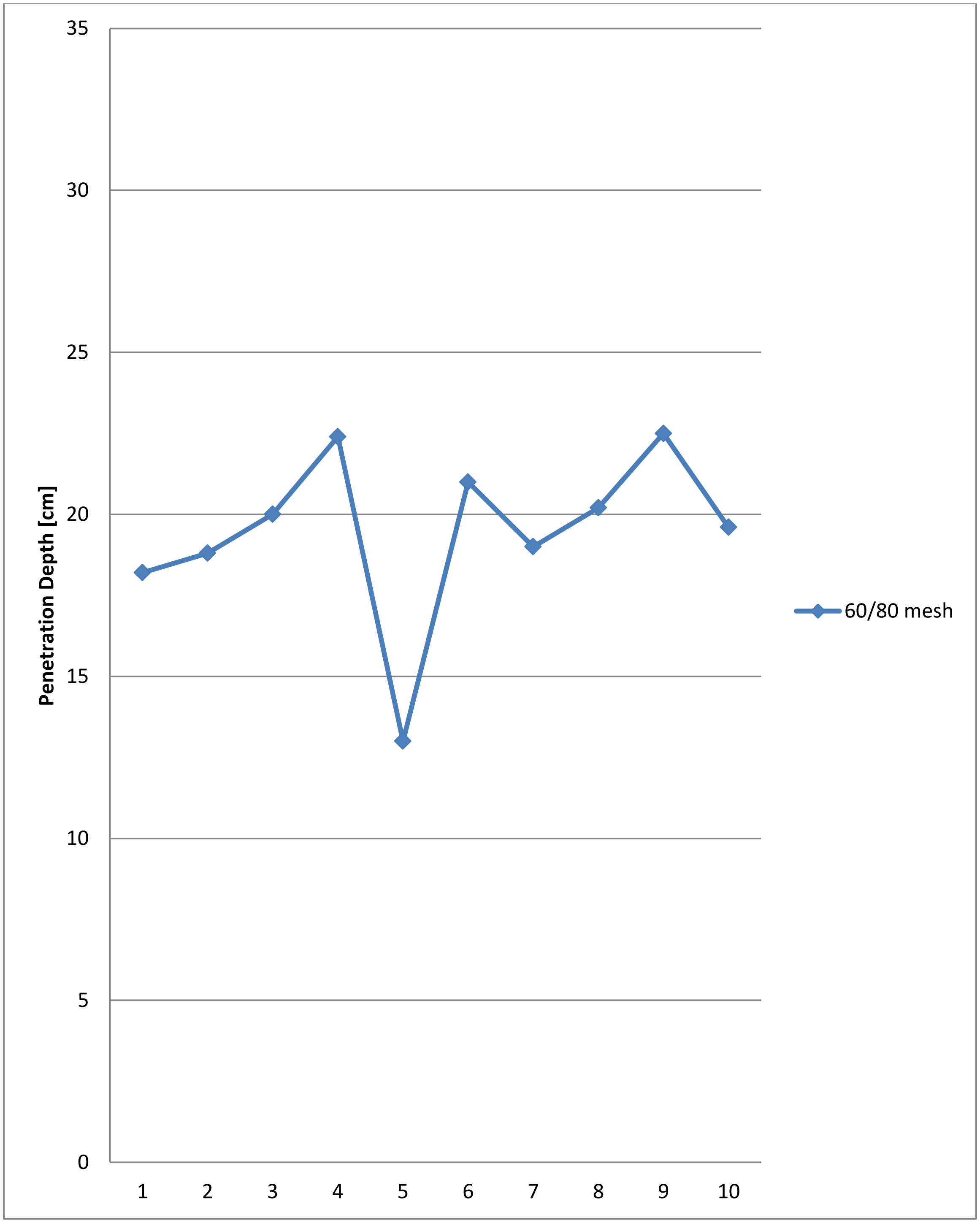


Figure 33 Penetration of 60/80 Mesh Sand with Ten 7.62x39 Rounds

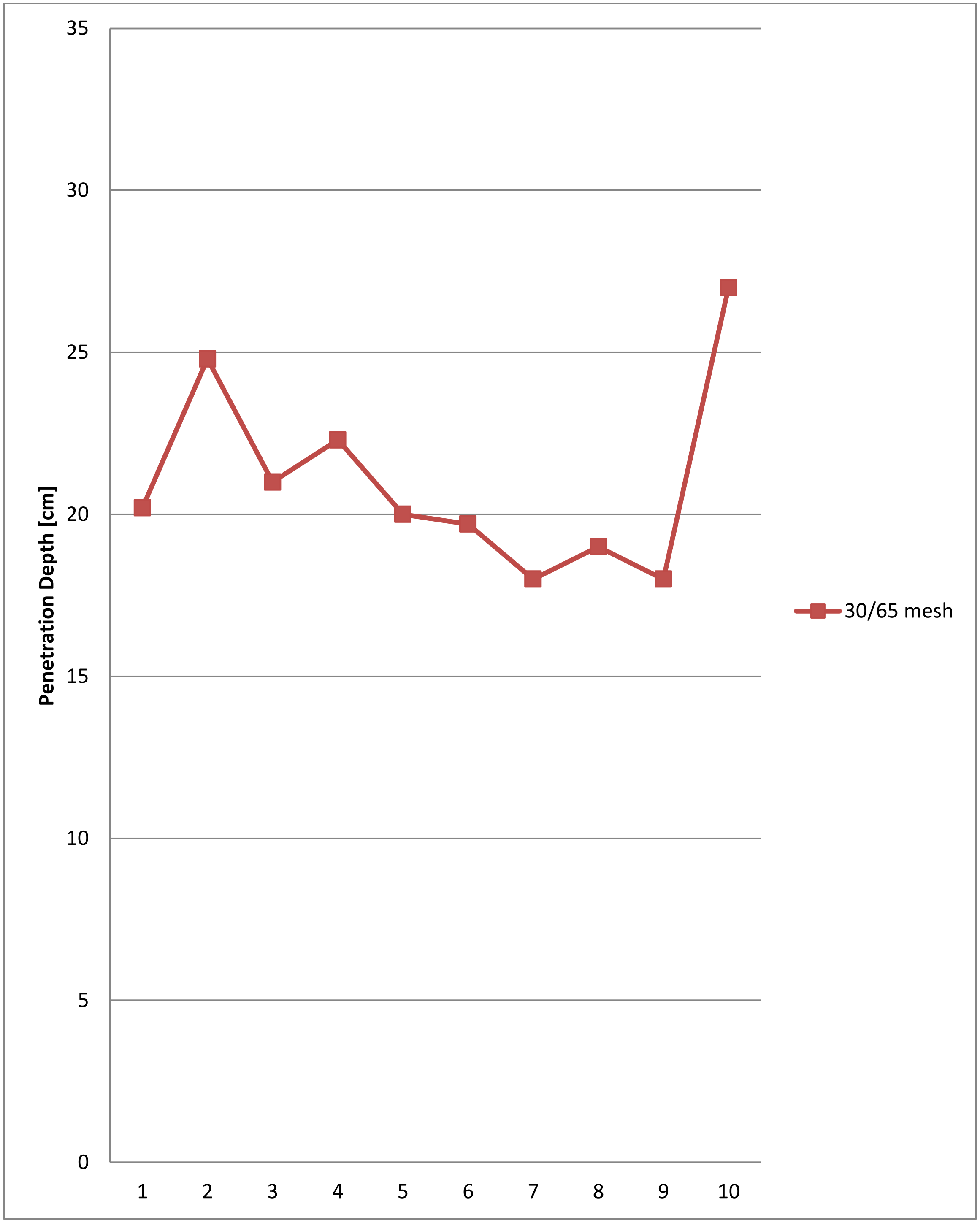


Figure 34 Penetration of 30/65 Mesh Sand with Ten 7.62x39 Rounds

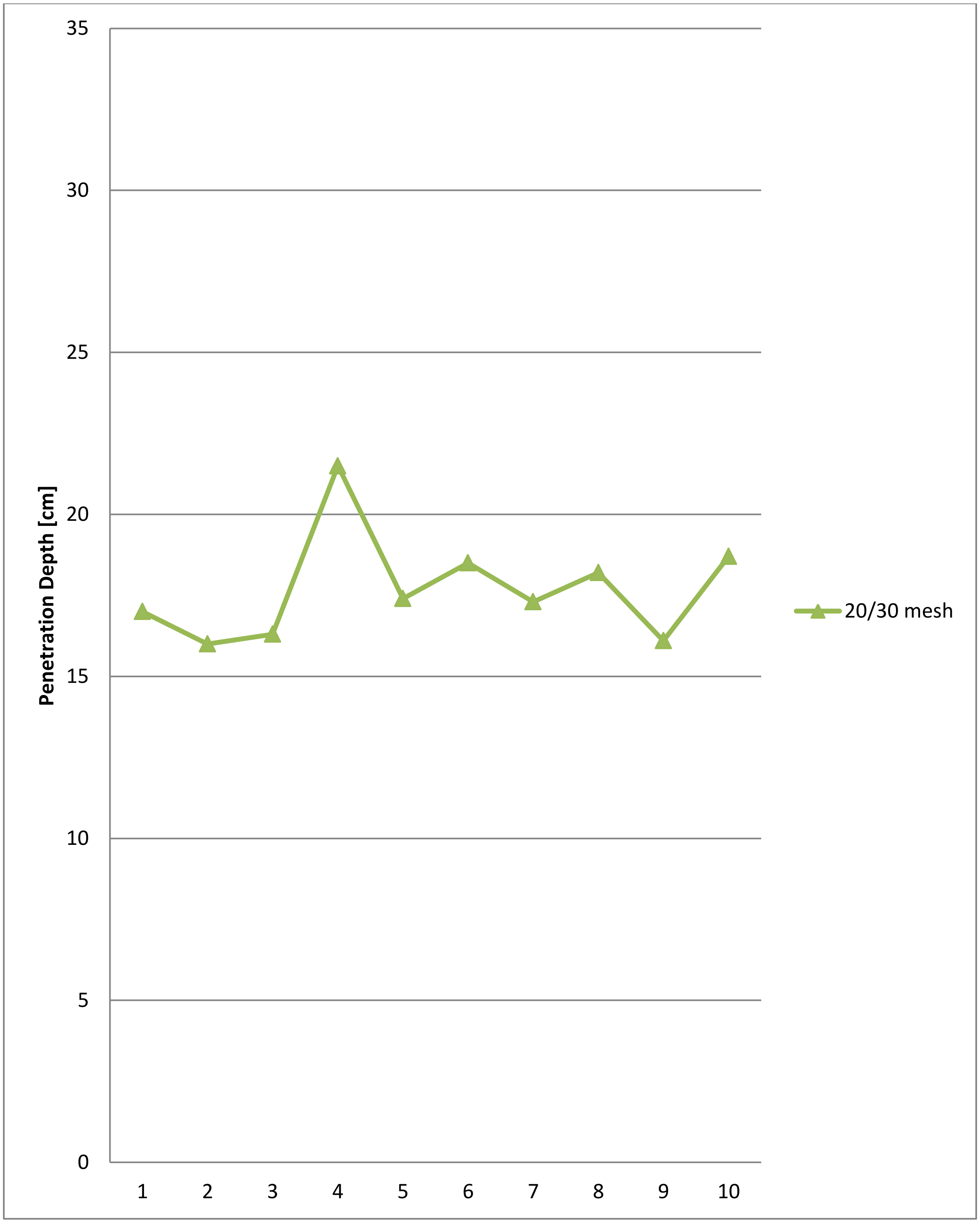


Figure 35 Penetration of 20/30 Mesh Sand with Ten 7.62x39 Rounds

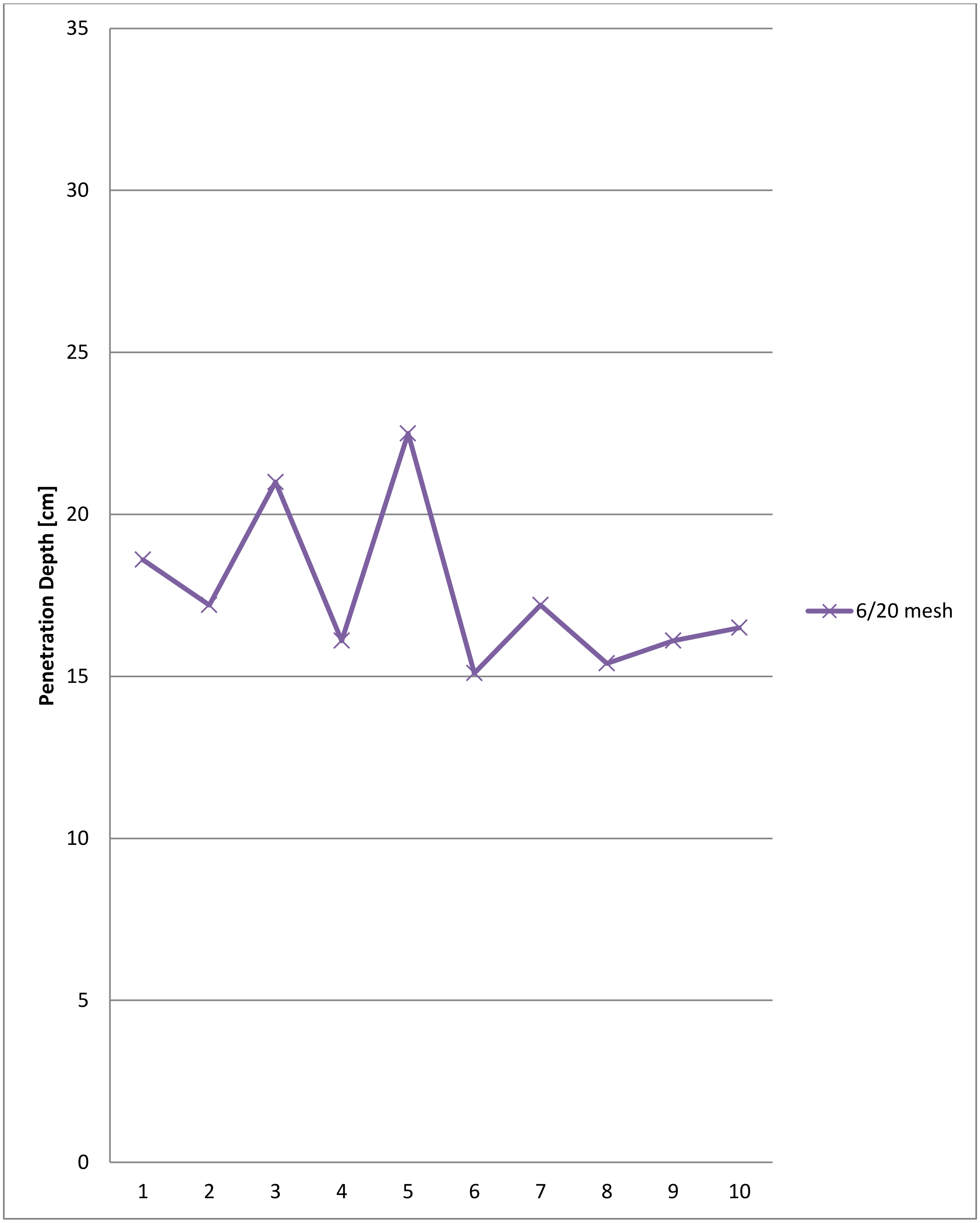


Figure 36 Penetration of 6/20 Mesh Sand with Ten 7.62x39 Rounds

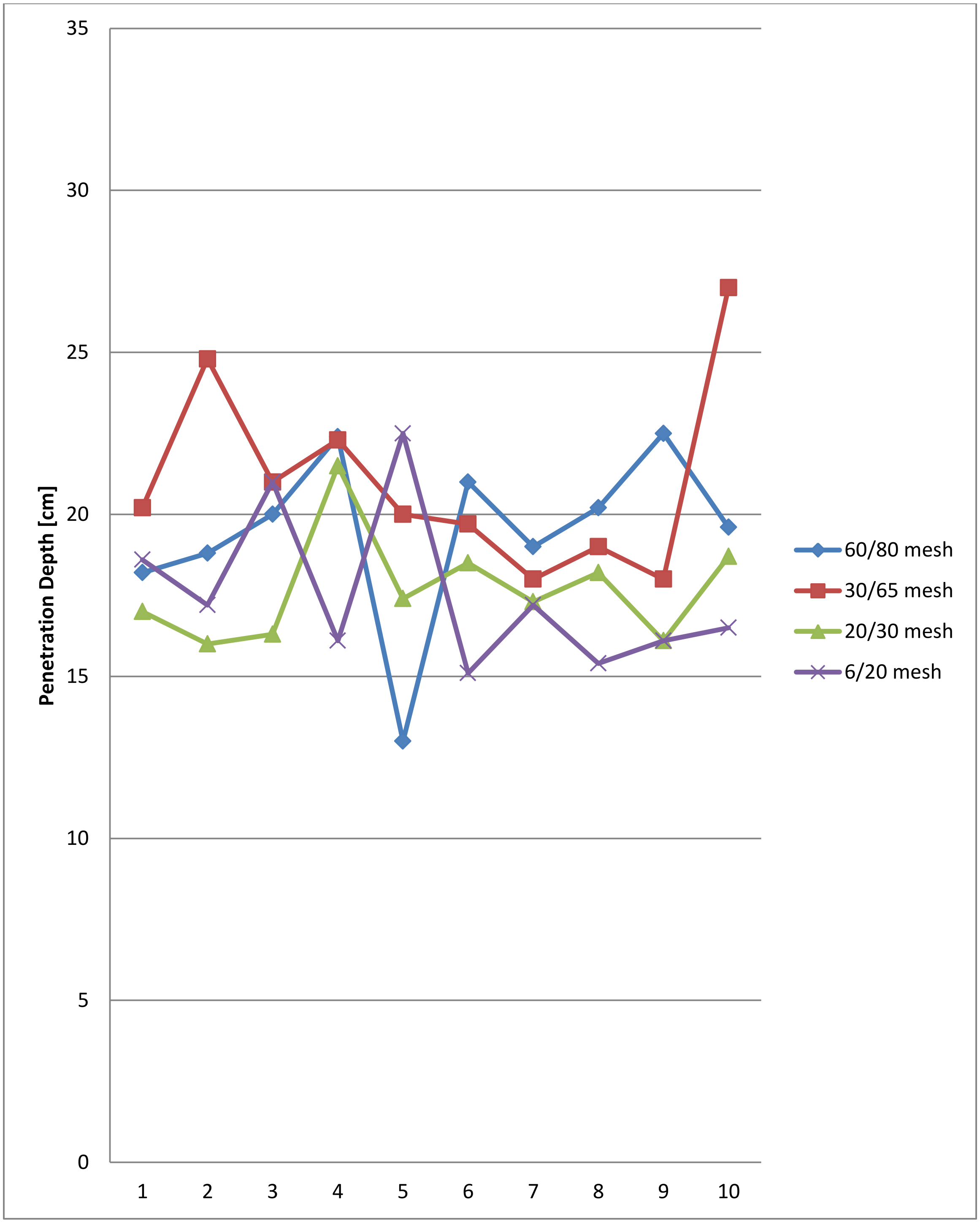


Figure 37 Penetration of Each Grade of Sand with Ten 7.62x39 Rounds

There is clearly a fair amount of experimental scatter. In order to better depict any possible trends in the data, the following, Figure 38, shows average penetration of the 7.62x39 round plotted against the average grain size of each material.

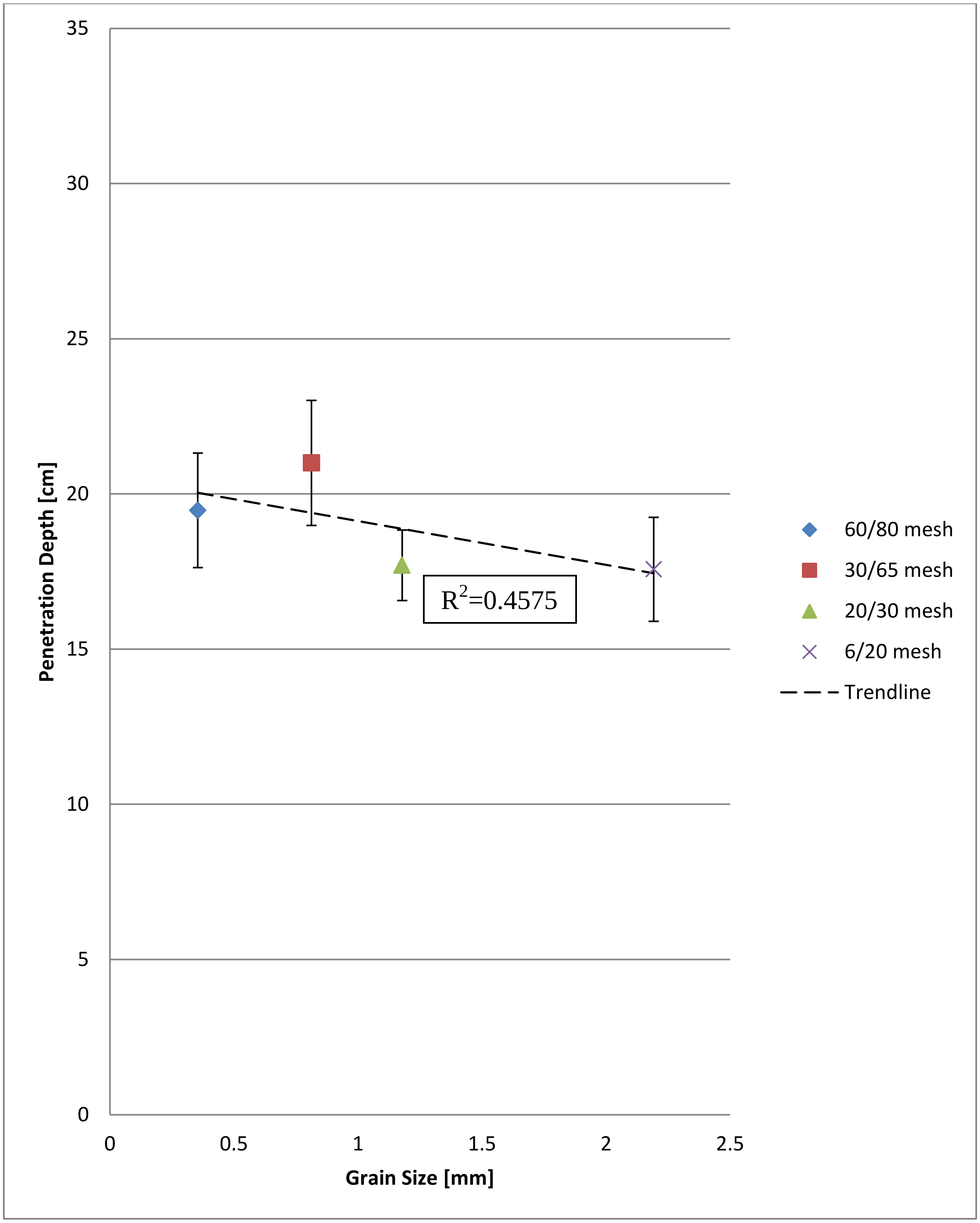


Figure 38 Average Penetration of the 7.62x39 Round vs. Average Grain Size

This shows a very slight trend down from left to right illustrating decreasing penetration depth with increasing grain size, but this apparent trend might not be statistically significant due to the low R^2 value. The error bars represent the 97%

confidence interval on which the mean penetration is expected to exist. The collected rounds are shown below in Figure 39. The rounds are ordered by the media used to stop them vertically with increasing grain size from top row to bottom row.

Figure 39 Post-Impact 7.62x39 Bullets, Top to Bottom is Finest to Coarsest

4.1.2 The 7.62x39 Round into Rubber

The penetration of the 7.62x39 round in the various rubbery media, as measured, is shown below in Figures 40-42. The compilation of all 7.62x39 tests into rubber is shown in Figure 43. Performing a one-way ANOVA test on the 7.62x39 penetration into rubber data gives a probability of 99.99% that penetration does depend on grain size.

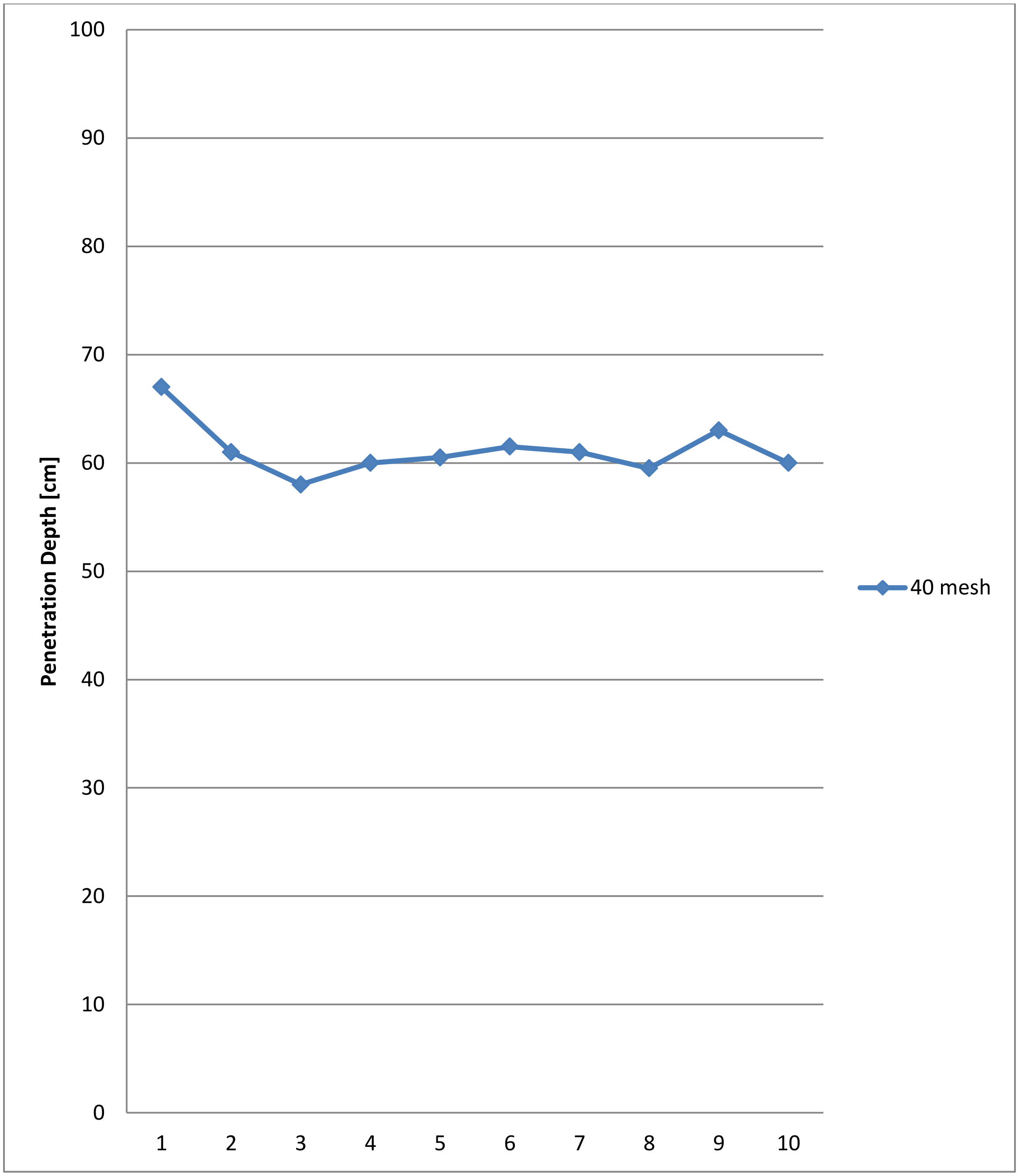


Figure 40 Penetration of 40 Mesh Rubber with Ten 7.62x39 Rounds

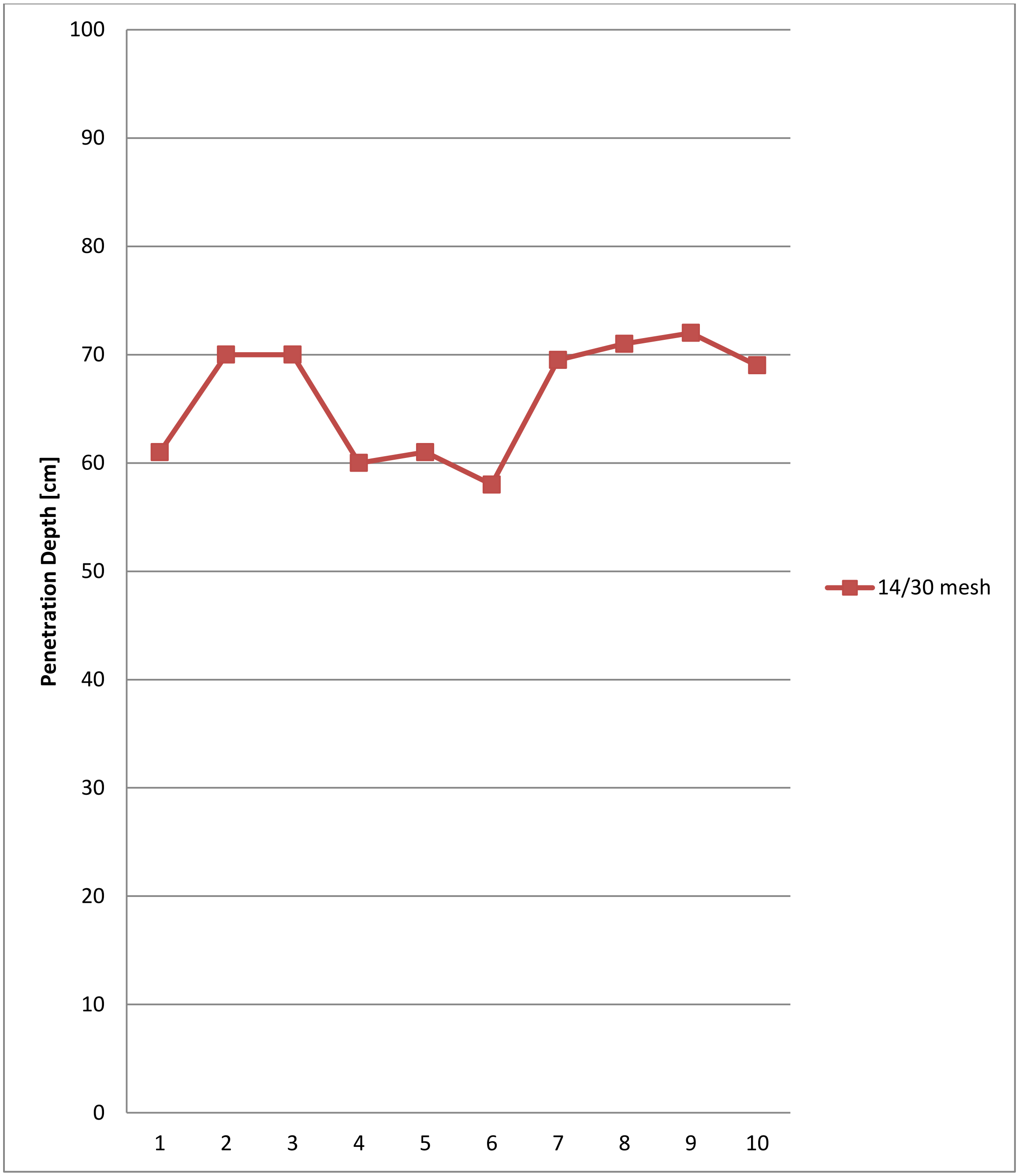


Figure 41 Penetration of 14/30 Mesh Rubber with Ten 7.62x39 Rounds

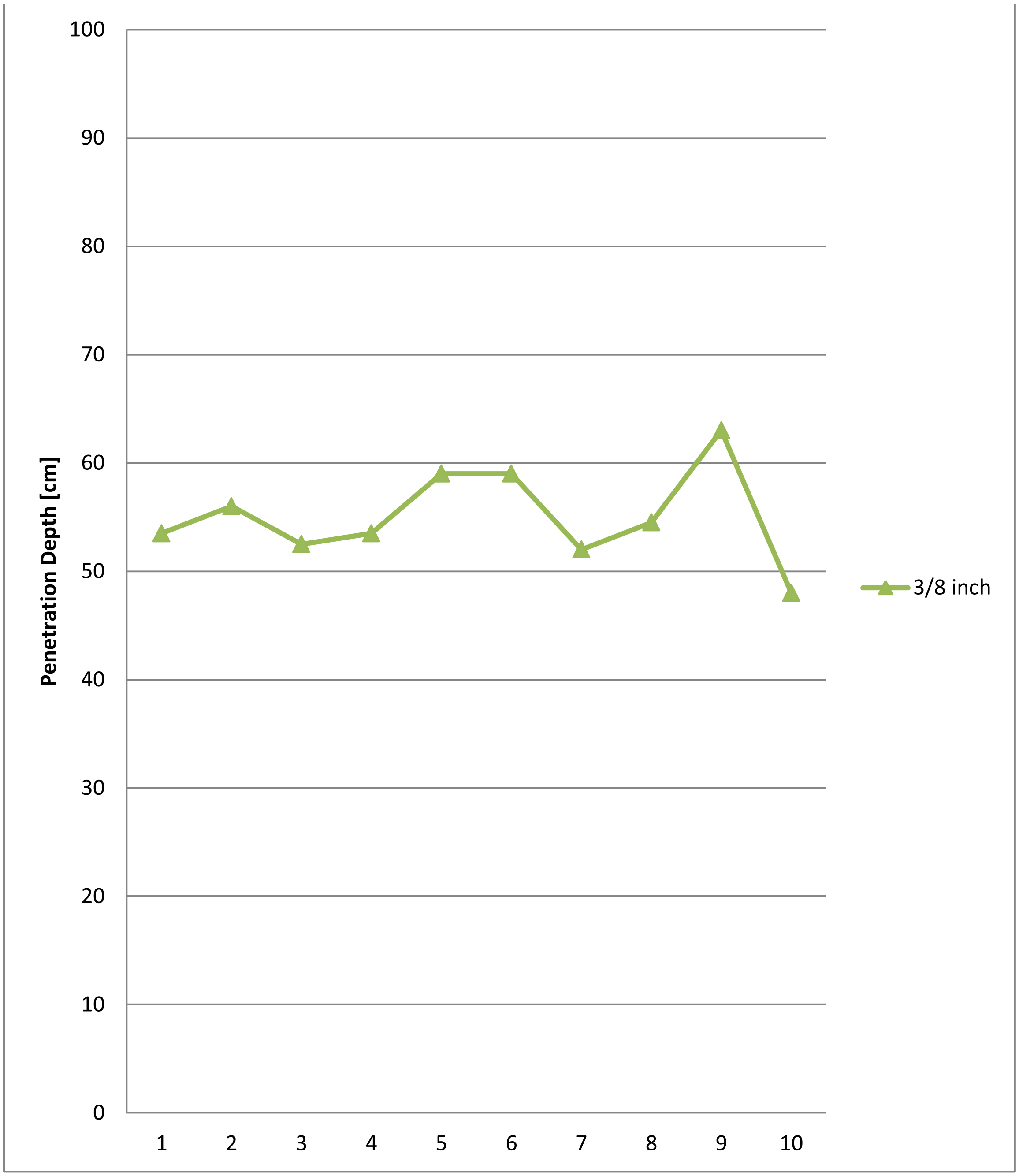


Figure 42 Penetration of 3/8 Inch Rubber with Ten 7.62x39 Rounds

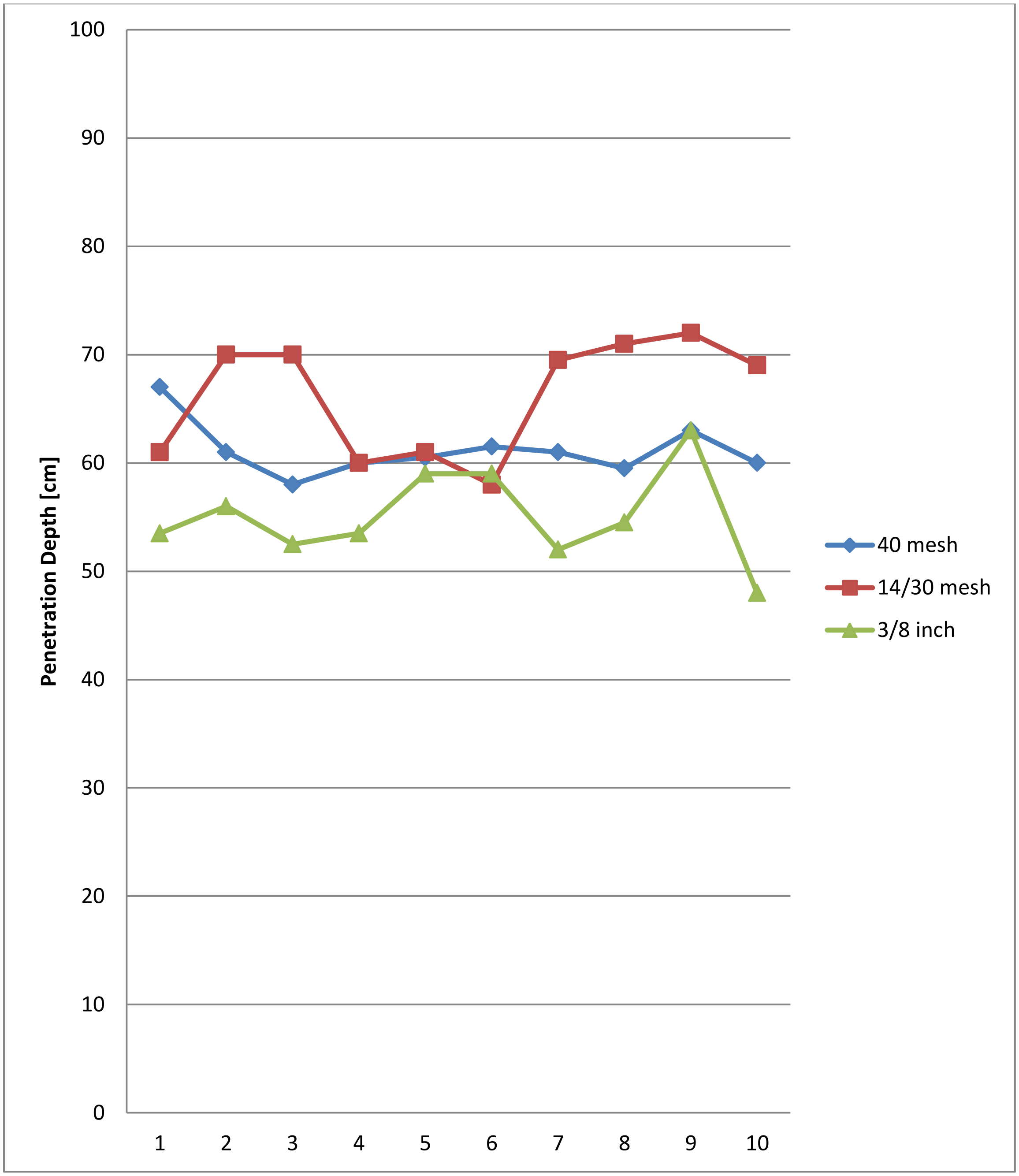


Figure 43 Penetration of Each Grade of Rubber with Ten 7.62x39 Rounds

There is a noticeable fact that shows through the 14/30 data. The penetration is either near 60 or 70 cm, but not really within the 60-70 cm range. This will be addressed in Chapter 5.

Figure 44, shows average penetration of the 7.62x39 round plotted against the average grain size of each rubbery material.

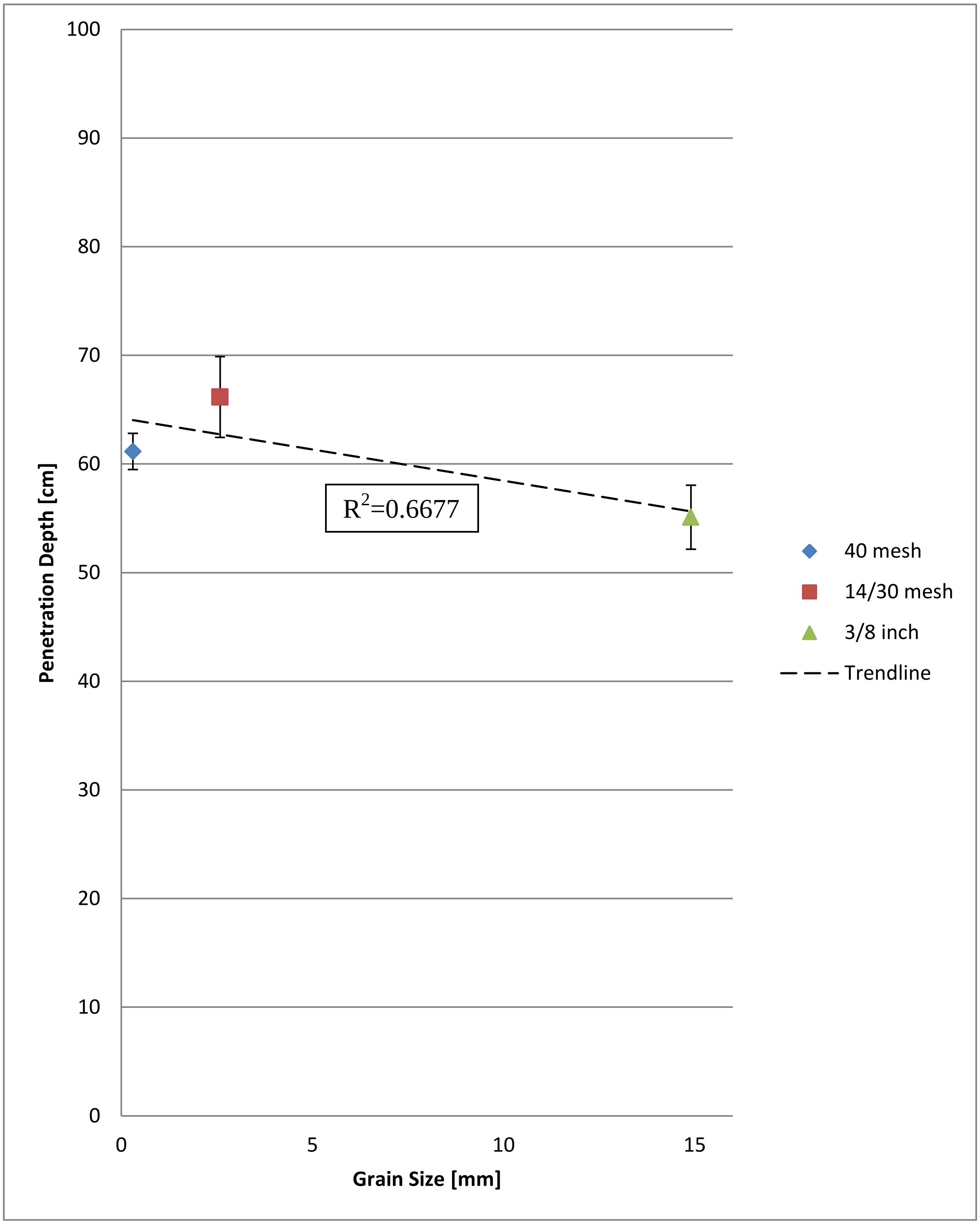


Figure 44 Average Penetration of 7.62x39 Round vs. Average Grain Size of Rubber

The error bars represent the 97% confidence interval on which the mean penetration is expected to exist. Here, the R^2 value of the trend-line to the data is still too low to make assertions about the penetration being linearly or otherwise dependent on grain size. The collected rounds are shown below in Figure 45. The rounds are ordered by the media used to stop them vertically with increasing grain size from top row to bottom row.

Figure 45 Post-Impact 7.62x39 Bullets, Top to Bottom is Finest to Coarsest

4.2 The 9mm Round

The 9mm round was tested for penetration in the four sizes of sand and the three sizes of rubber.

4.2.1 The 9mm Round into Sand

The penetration of the 9mm round in the various sandy media, as measured, is shown below in Figures 46-49. The compilation of all 9mm tests into sand is shown in Figure 50. Performing a one-way ANOVA test on the 9mm penetration into sand data gives a probability of nearly 100% that penetration does depend on grain size.

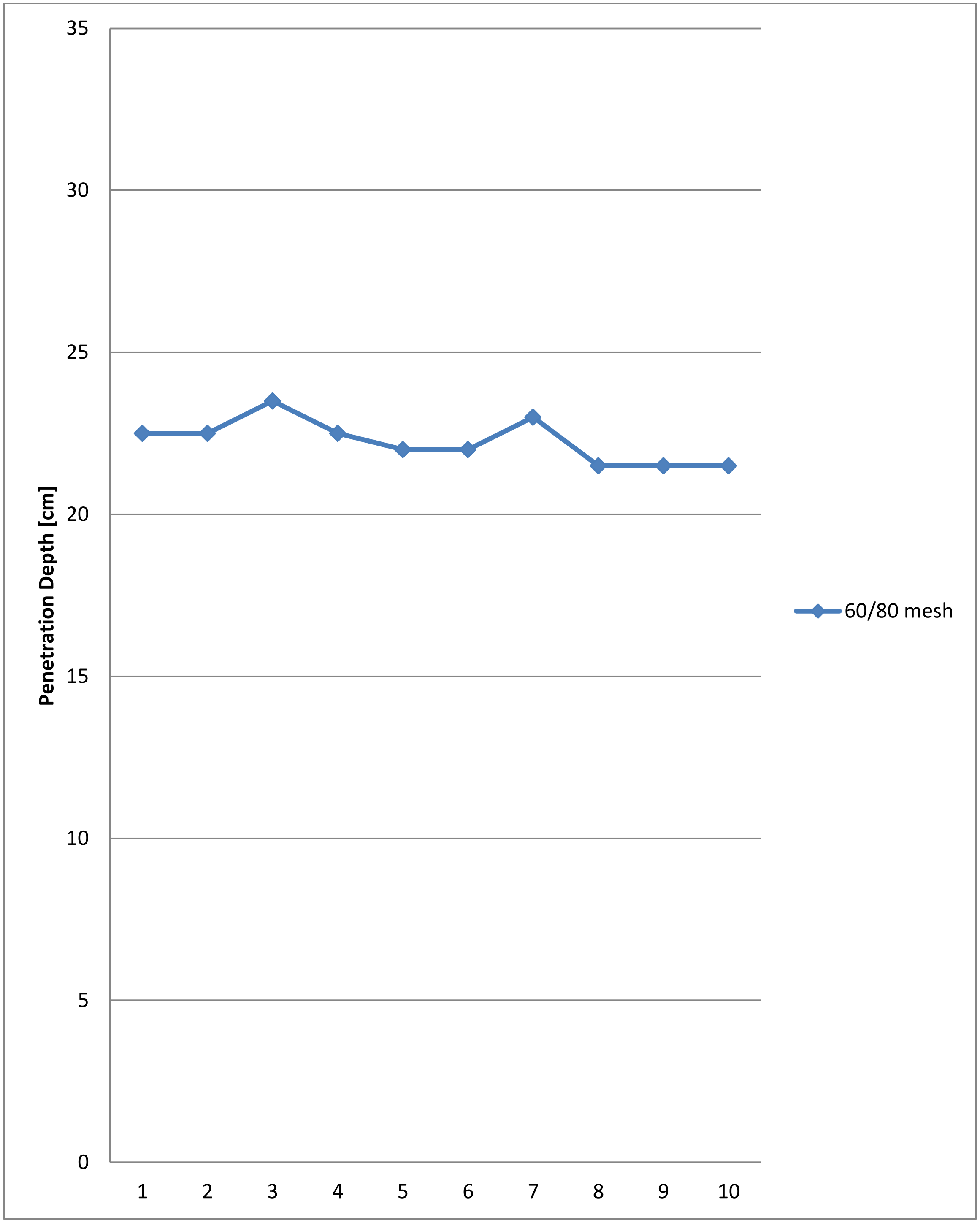


Figure 46 Penetration of 60/80 Mesh Sand with Ten 9mm Rounds

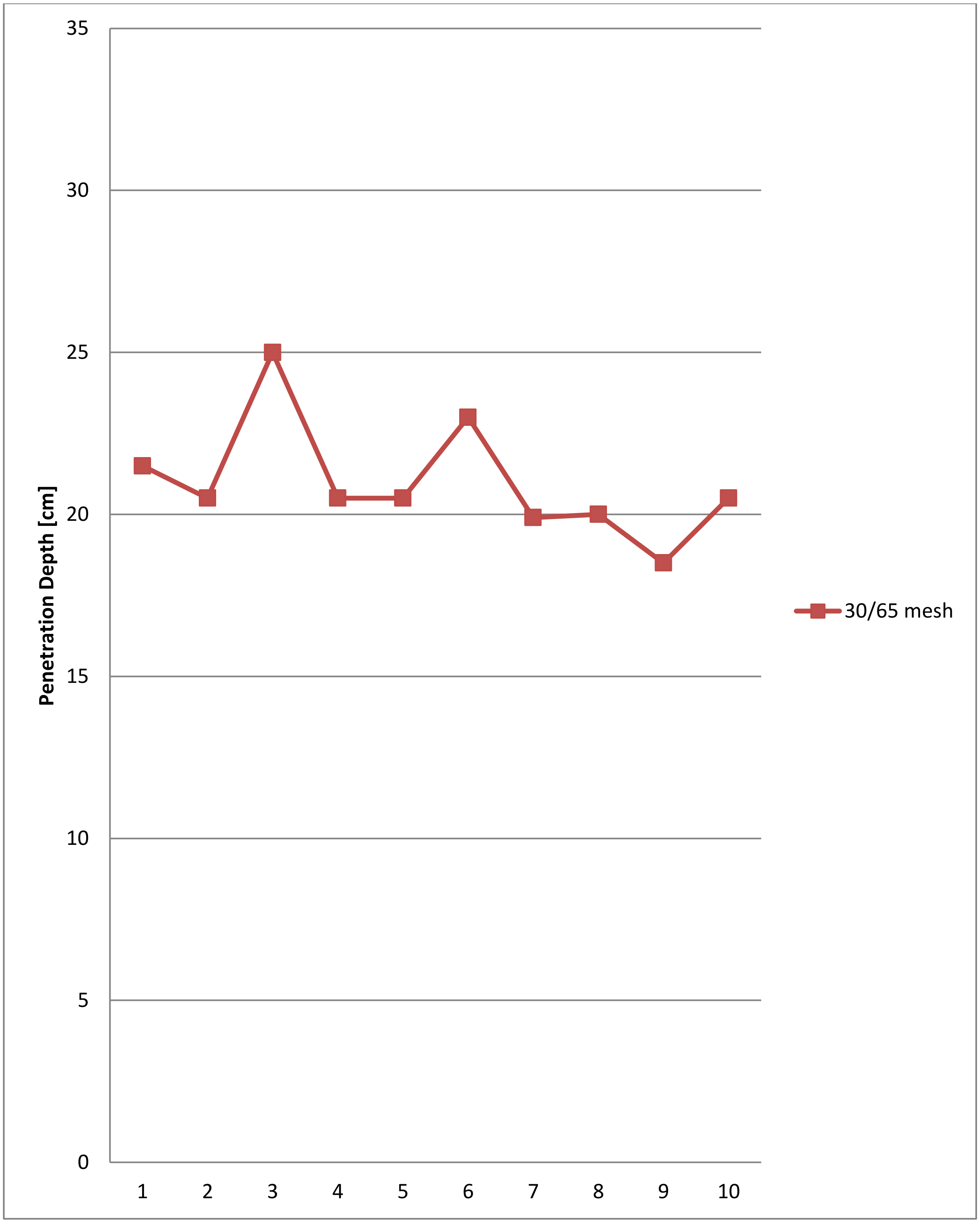


Figure 47 Penetration of 30/65 Mesh Sand with Ten 9mm Rounds

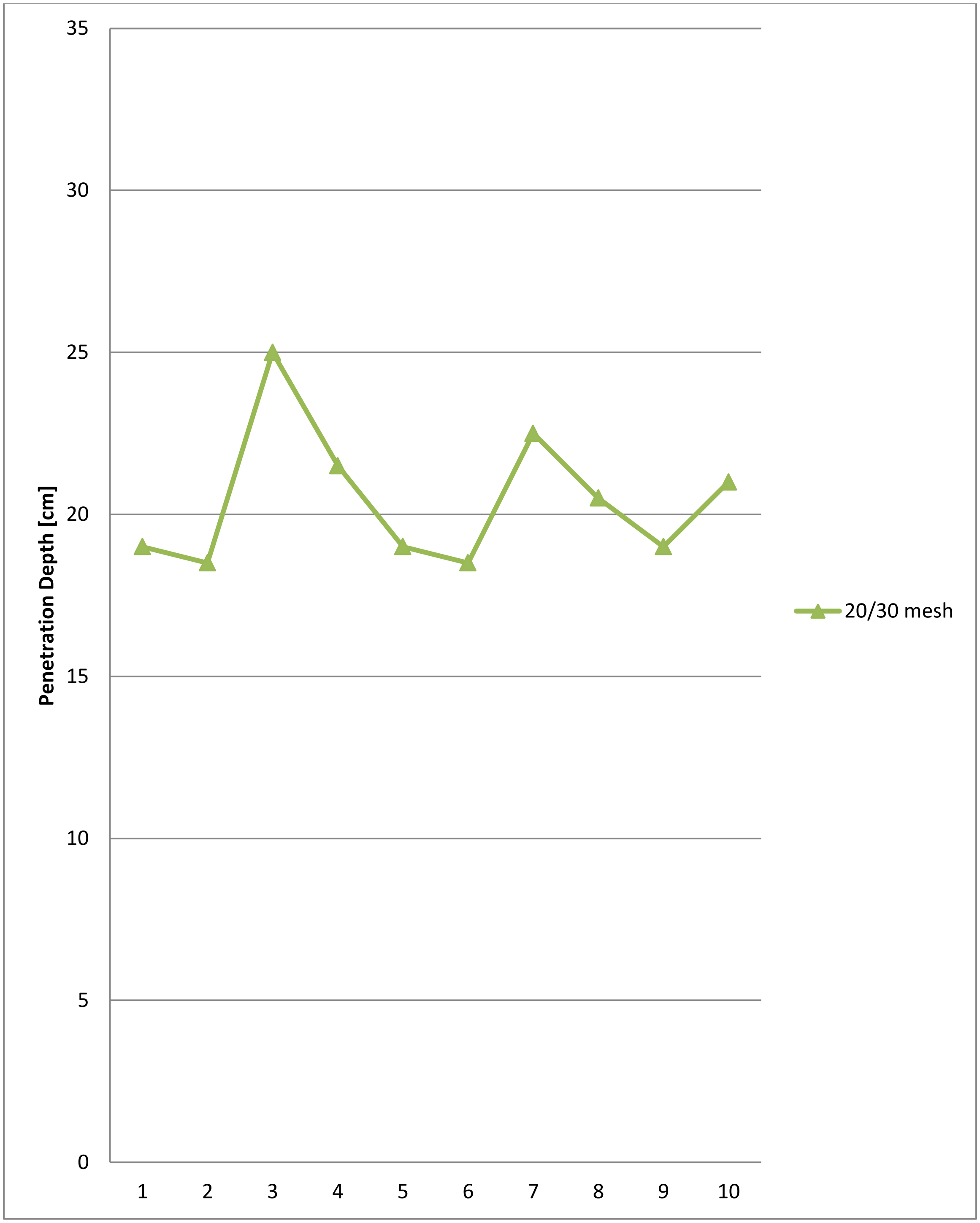


Figure 48 Penetration of 23/30 Mesh Sand with Ten 9mm Rounds

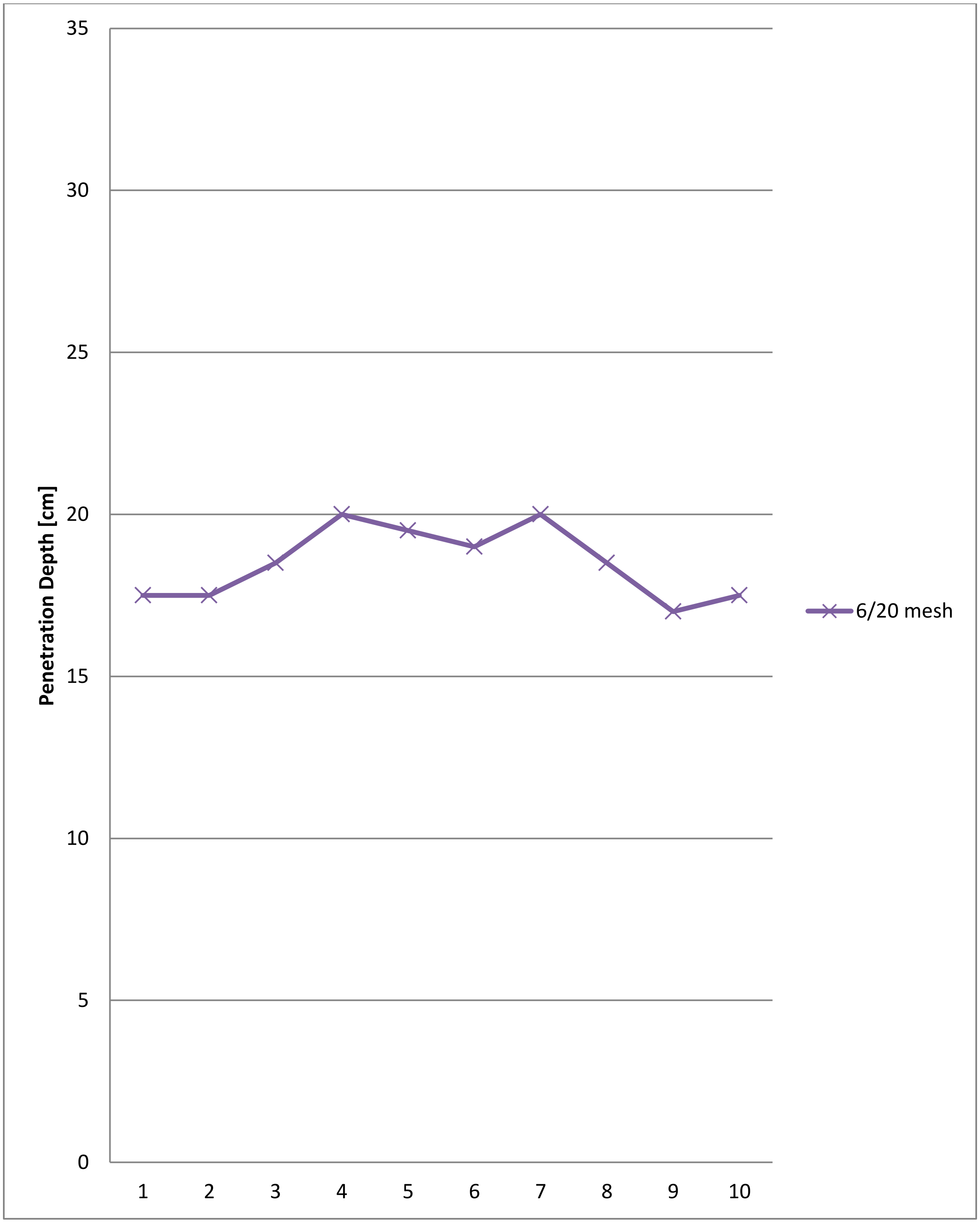


Figure 49 Penetration of 6/20 Mesh Sand with Ten 9mm Rounds

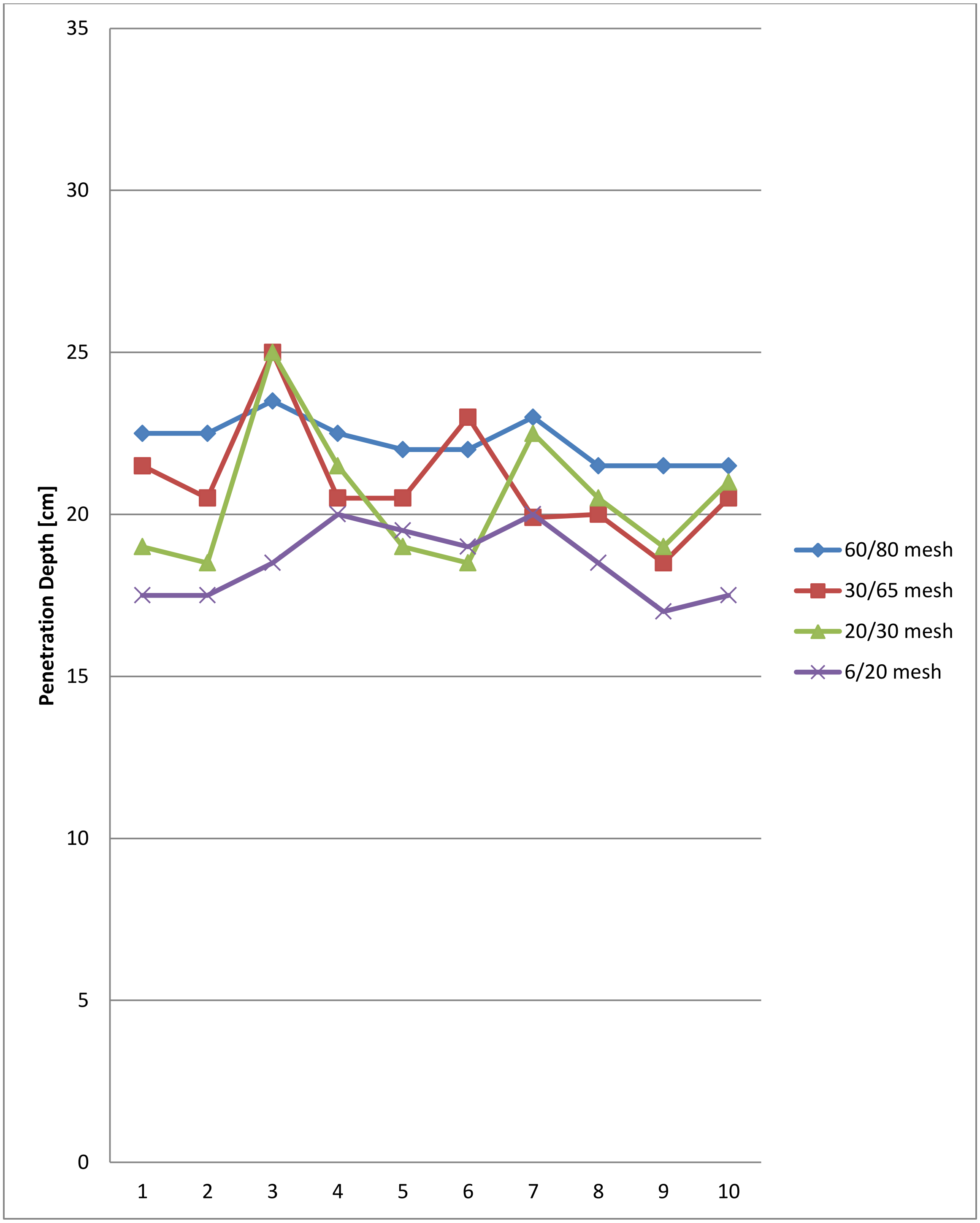


Figure 50 Penetration of Each Grade of Sand with Ten 9mm Rounds

There is, again, clearly a fair amount of experimental scatter. In order to better depict any possible trends in the data, the following Figure 51 shows average penetration of the 9mm round plotted against the average grain size of each material.

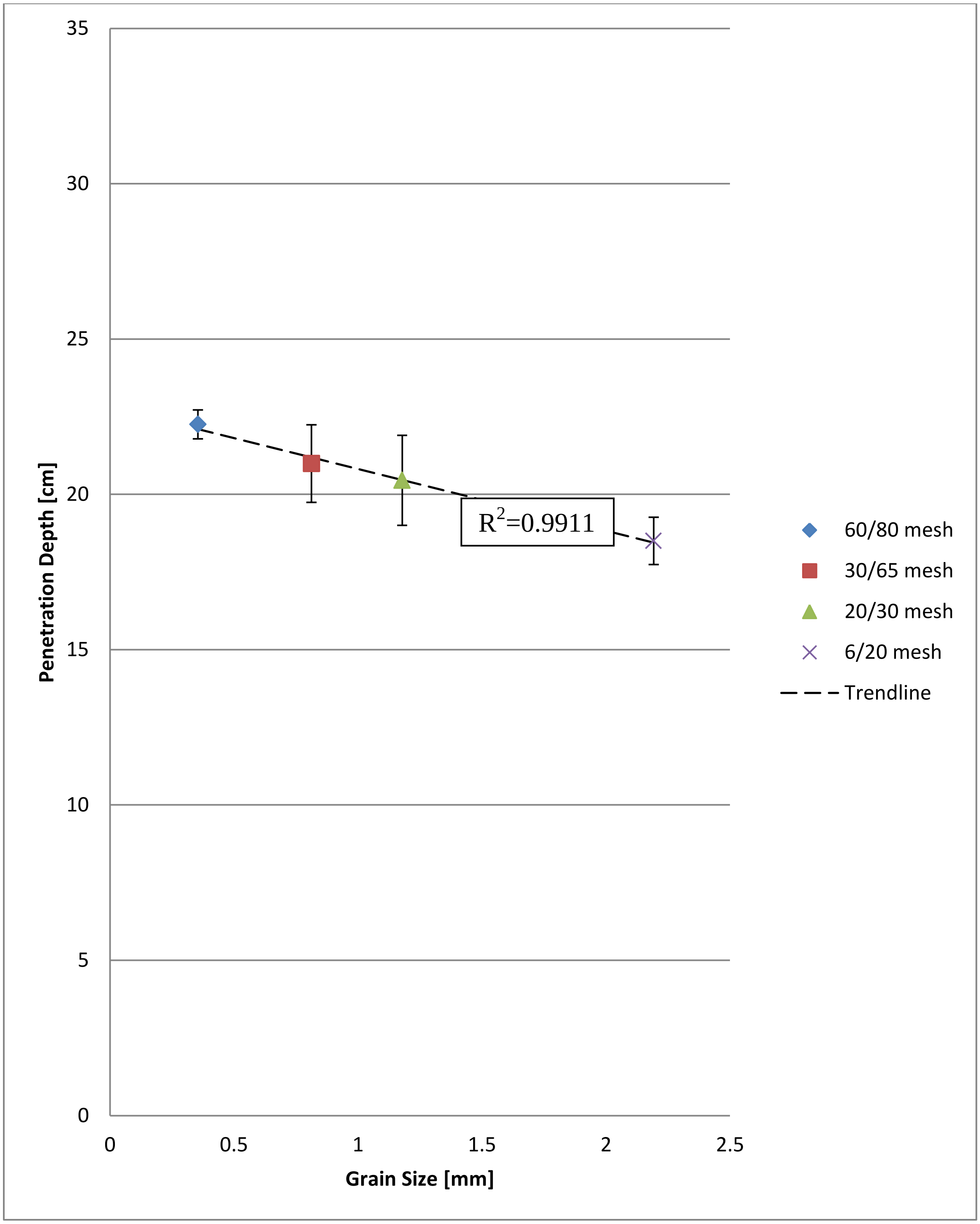


Figure 51 Average Penetration of the 9mm Round vs. Average Grain Size

Here, the trend is very clear: the larger the grain size the less penetration (down from left to right), and with the R^2 value close to 1, there is a good fit of the data to the linear trend-line. The error bars represent the 97% confidence interval on which the mean penetration is expected to exist. The collected rounds are shown below in Figure 52. The rounds are ordered by the media used to stop them vertically with increasing grain size from top row to bottom row.

Figure 52 Post-Impact 9mm Bullets, Top to Bottom is Finest to Coarsest

It can be noticed that some bullets appear untouched on the sides while others show significant wear. This is because every bullet has both, a relatively untouched side and a side with wear. This will be discussed more in Chapter 5.

4.2.2 The 9mm Round into Rubber

The penetration of the 9mm round in the various rubbery media, as measured, is shown below in Figures 53-55. The compilation of all 7.62x39 tests into rubber is shown in Figure 56. Performing a one-way ANOVA test on the 9mm penetration into sand data gives a probability of 99.99% that penetration does depend on grain size.

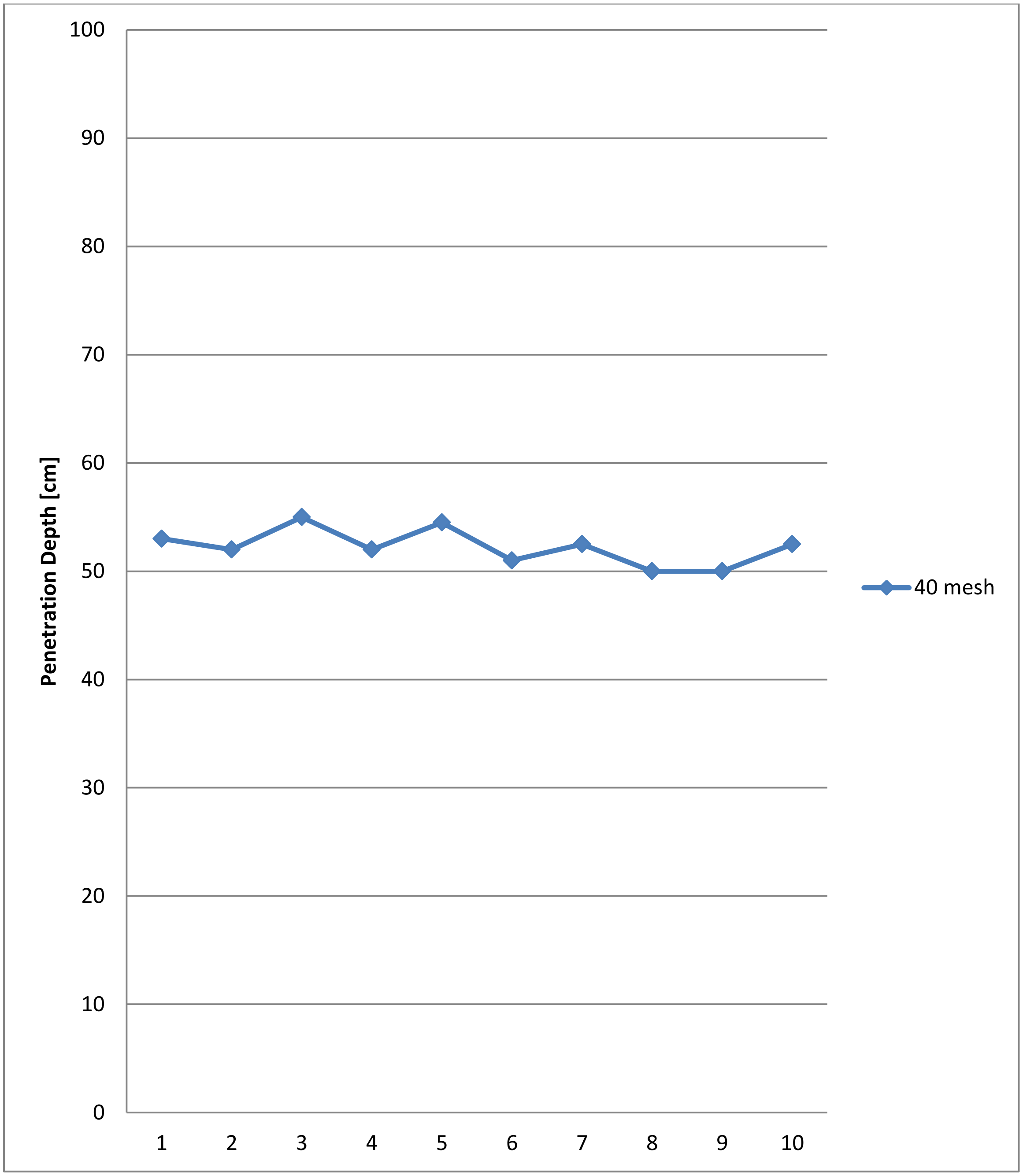


Figure 53 Penetration of 40 Mesh Rubber with Ten 9mm Rounds

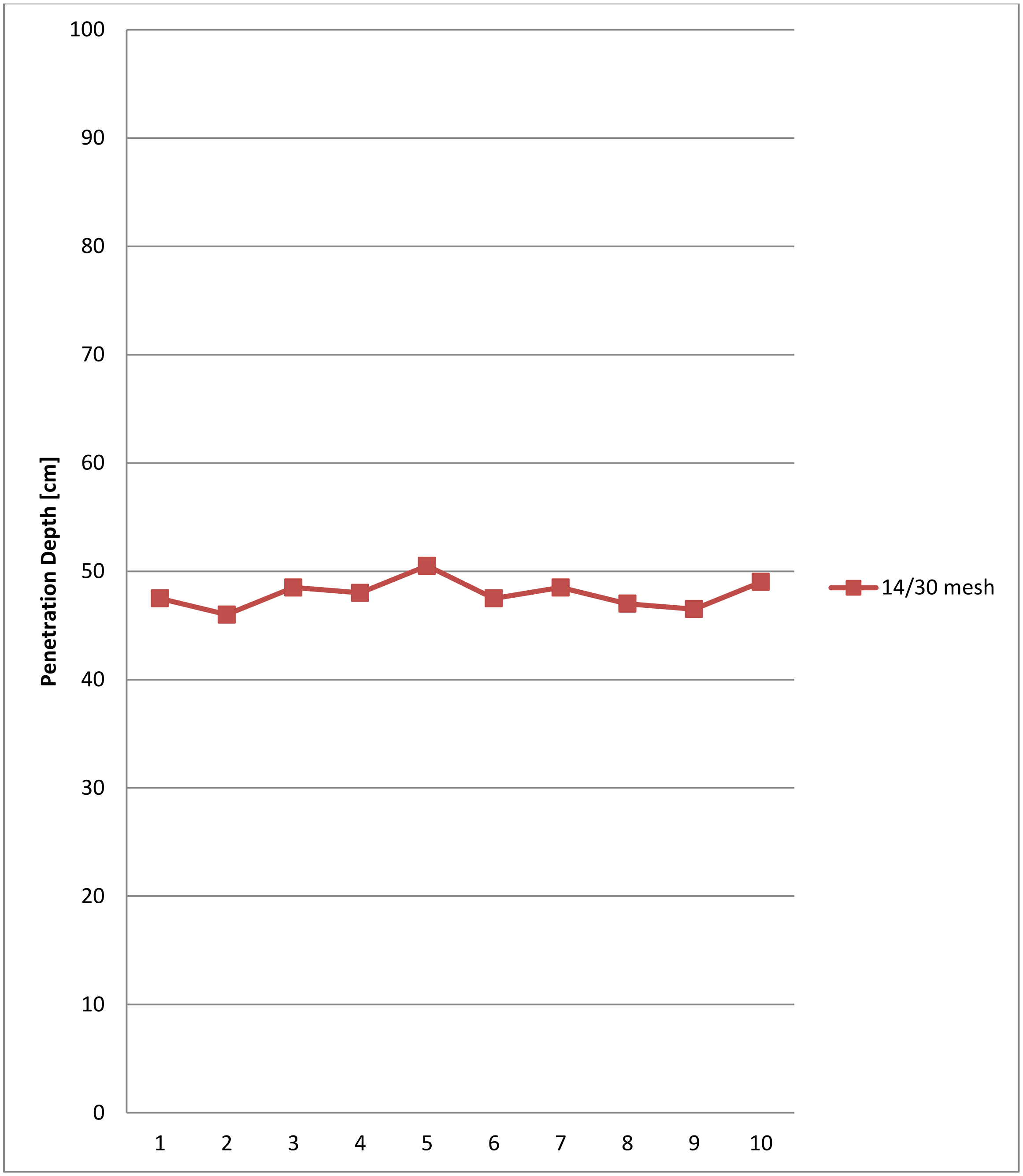


Figure 54 Penetration of 14/30 Mesh Rubber with Ten 9mm Rounds

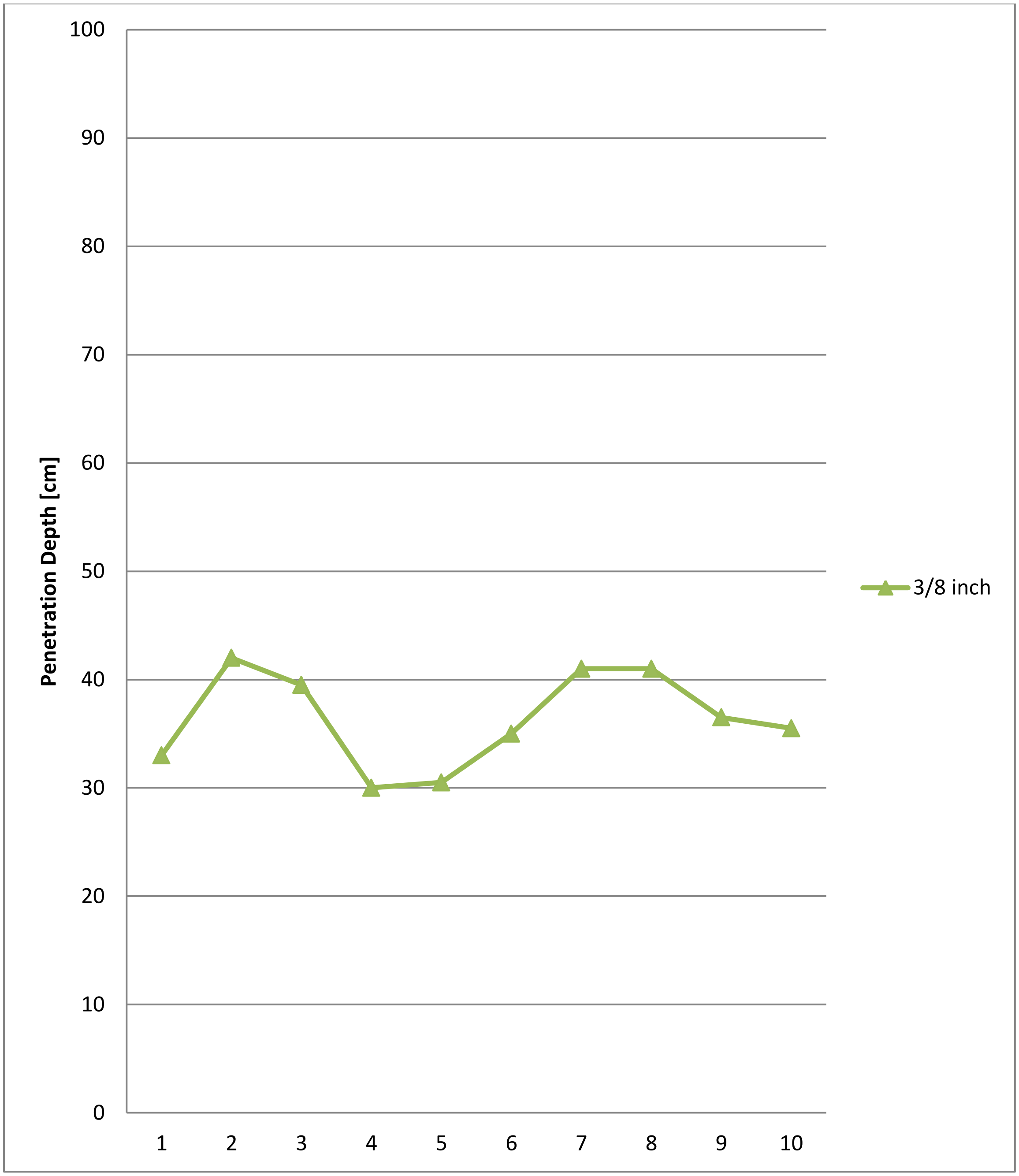


Figure 55 Penetration of 3/8 Inch Rubber with Ten 9mm Rounds

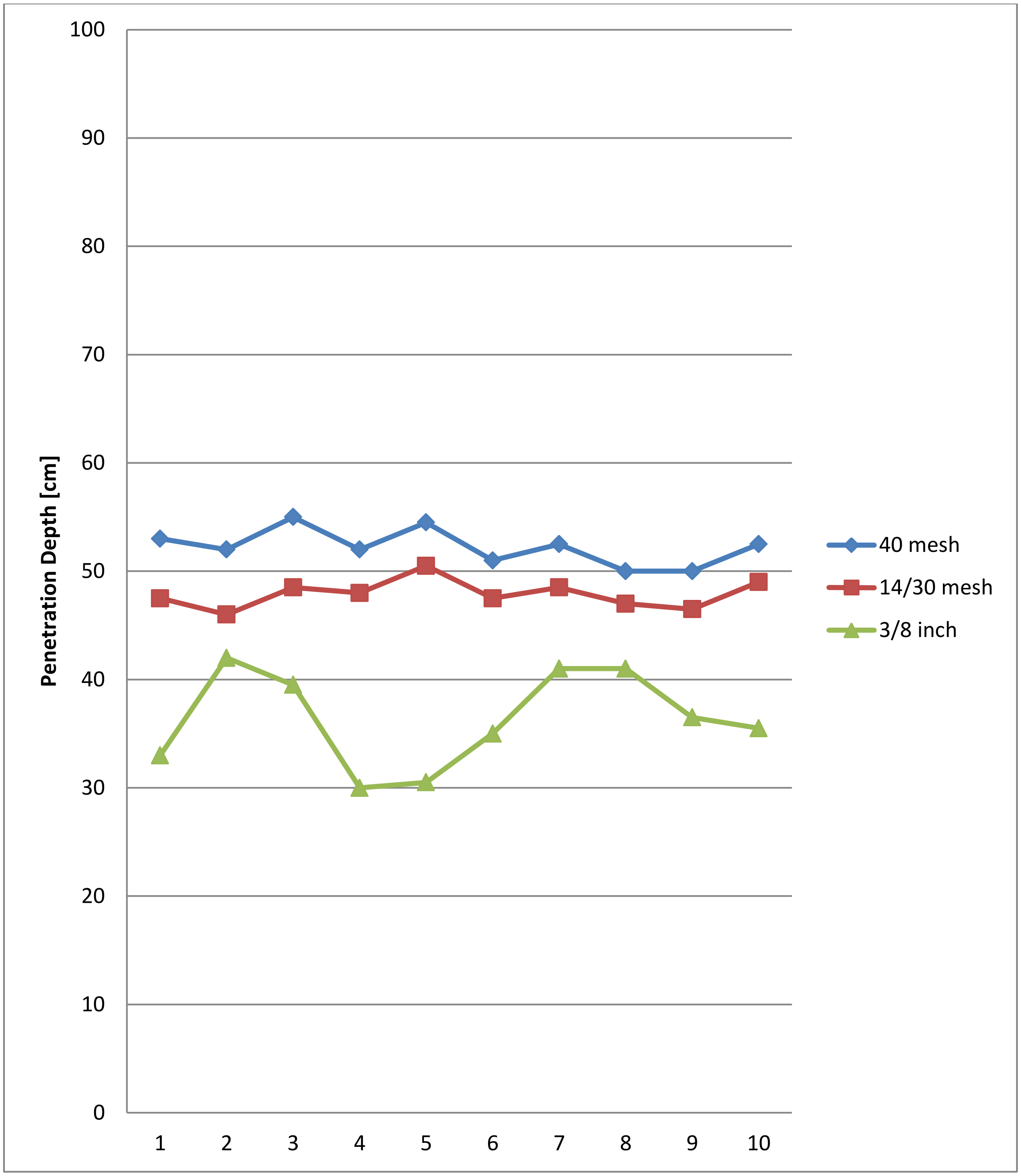


Figure 56 Penetration of Each Grade of Rubber with Ten 9mm Rounds

Figure 57, below, shows average penetration of the 9mm round plotted against the average grain size of each material.

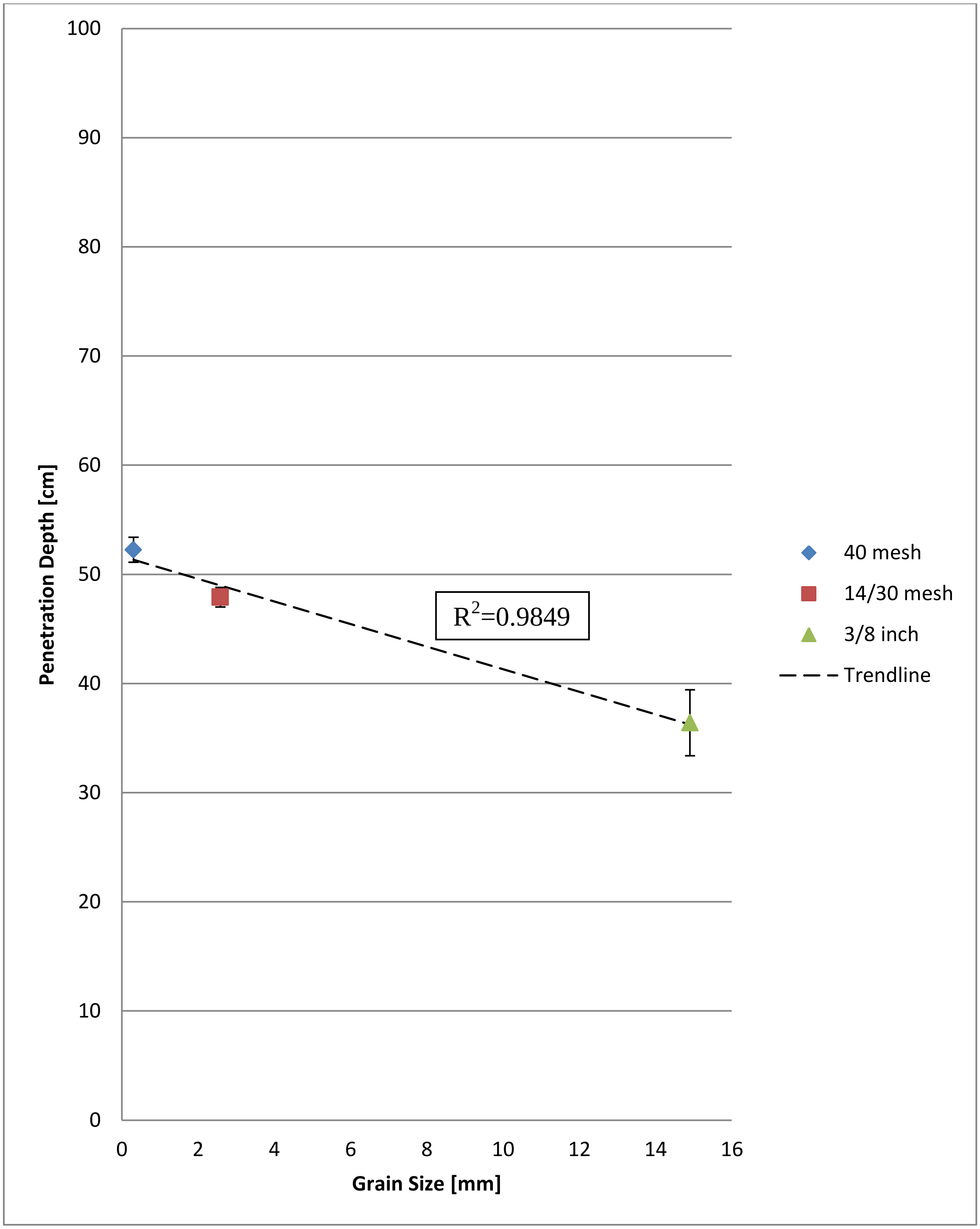


Figure 57 Average Penetration of 9mm Round vs. Average Grain Size of Rubber

Here, the trend is very clear: the larger the grain size the less penetration (down from left to right), and with the R^2 value close to 1, there is a good fit of the data to the linear trend-line. The error bars represent the 97% confidence interval on which the mean penetration is expected to exist.

The collected rounds are shown below in Figure 58. The rounds are ordered by the media used to stop them vertically with increasing grain size from top row to bottom row.

Figure 58 Post-Impact 9mm Bullets, Top to Bottom is Finest to Coarsest

4.3 Comparison of Both Rounds

The effects of varying velocity and size/shape of the round can be noticed best, when both rounds are plotted together. The following gives comparison with respect to grain size, velocities and the penetration achieved, both by average and by the individual shots.

4.3.1 Sand

It is clear that the 9mm rounds did not suffer the deformation and fragmentation that was apparent in the 7.62x39 rounds. This limits the conclusions that can be reached about the relationship of velocity, but the facts are still conclusive as will be discussed in

Chapters 5 and 6. Below in Figure 59, the average penetration of both rounds is plotted against the average grain sizes of the target material.

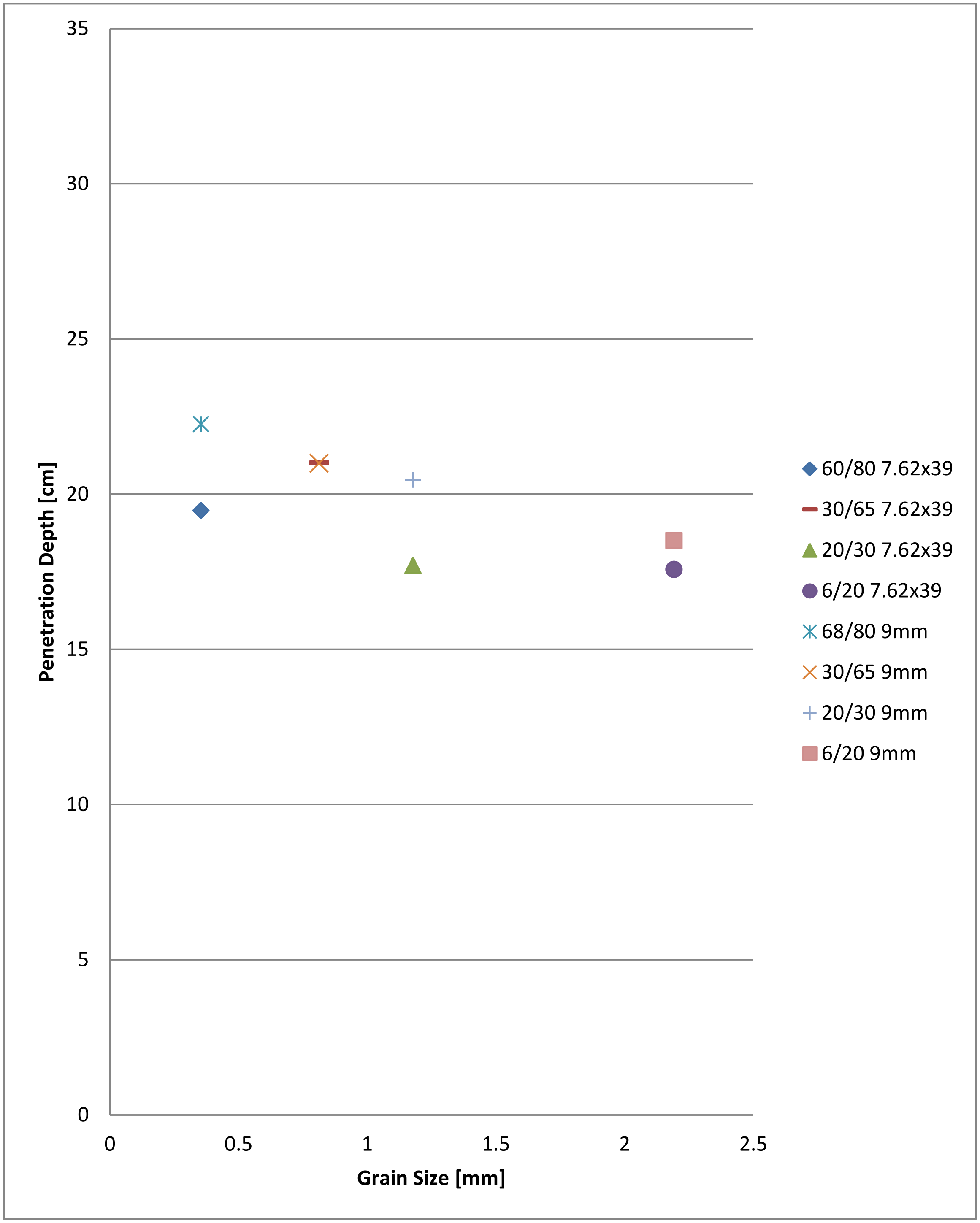


Figure 59 Average Penetration of Both Rounds vs. Average Grain Size

There is overlap of the two rounds in the case of the 30/65 mesh sand, but it can be noticed that on average, the 9mm round penetrated further or just as far as the (much faster) 7.62x39 round. Figure 60 (shown below) shows the relationship between velocity and penetration depth of the two rounds.

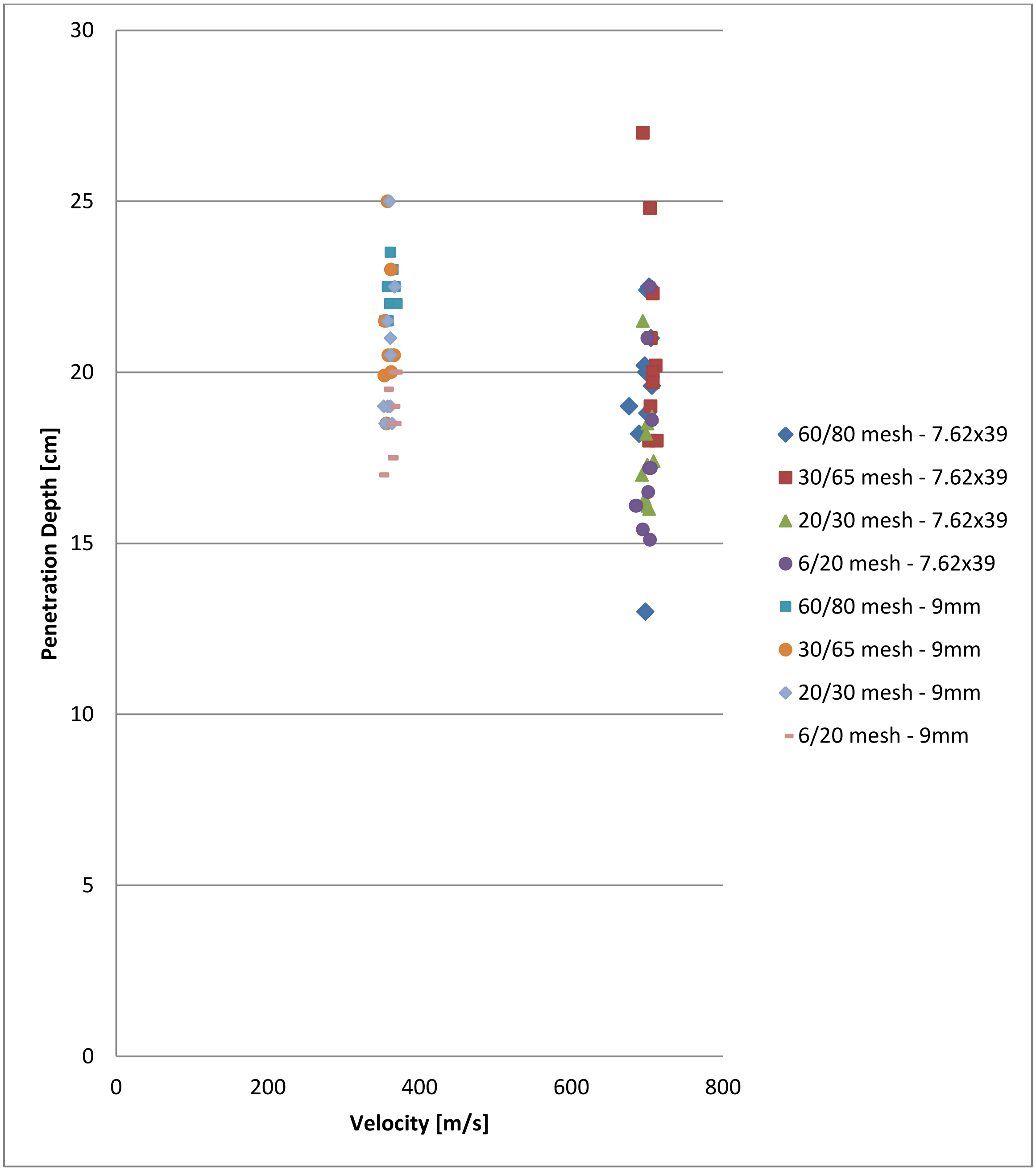


Figure 60 Penetration of Sand vs. Velocity

The graph shows a noticeable difference between the scatter of the 9mm rounds (on the left) and the 7.62x39 rounds (on the right), and it is, again, clear that on average, the penetration of the 9mm rounds is greater than that of the, much faster, 7.62x39 rounds. There are reasons for this apparent trend that may not allow for conclusions to be reached with regard to velocity dependent penetration. The collected rounds are shown again in Figures 61 and 62.

Figure 61 Post-Impact 7.62x39 Bullets, Top to Bottom is Finest to Coarsest

Figure 62 Post-Impact 9mm Bullets, Top to Bottom is Finest to Coarsest

There is no apparent fragmentation or deformation in the case of the 9mm as is present in the 7.62x39 rounds that were collected.

T-Tests were performed between all grain sizes of sand for both the 7.62x39 and 9mm rounds in order to determine if there is a significant difference of penetration between grain sizes (See Appendix E). It is shown that, in many instances, grains of different sizes allow significantly different penetration depths.

4.3.2 Rubber

The rubber shows trends that are not present in the case of the sand. There is greater average penetration into the rubber with the 7.62x39 round which does not hold true with the sand. Below in Figure 63, the average penetration of both rounds is plotted against the average grain sizes of the target material.

T-Tests were performed between all grain sizes of rubber for both the 7.62x39 and 9mm rounds in order to determine if there is a significant difference of penetration between grain sizes. It is shown that, in many instances, grains of different sizes allow significantly different penetration depths.

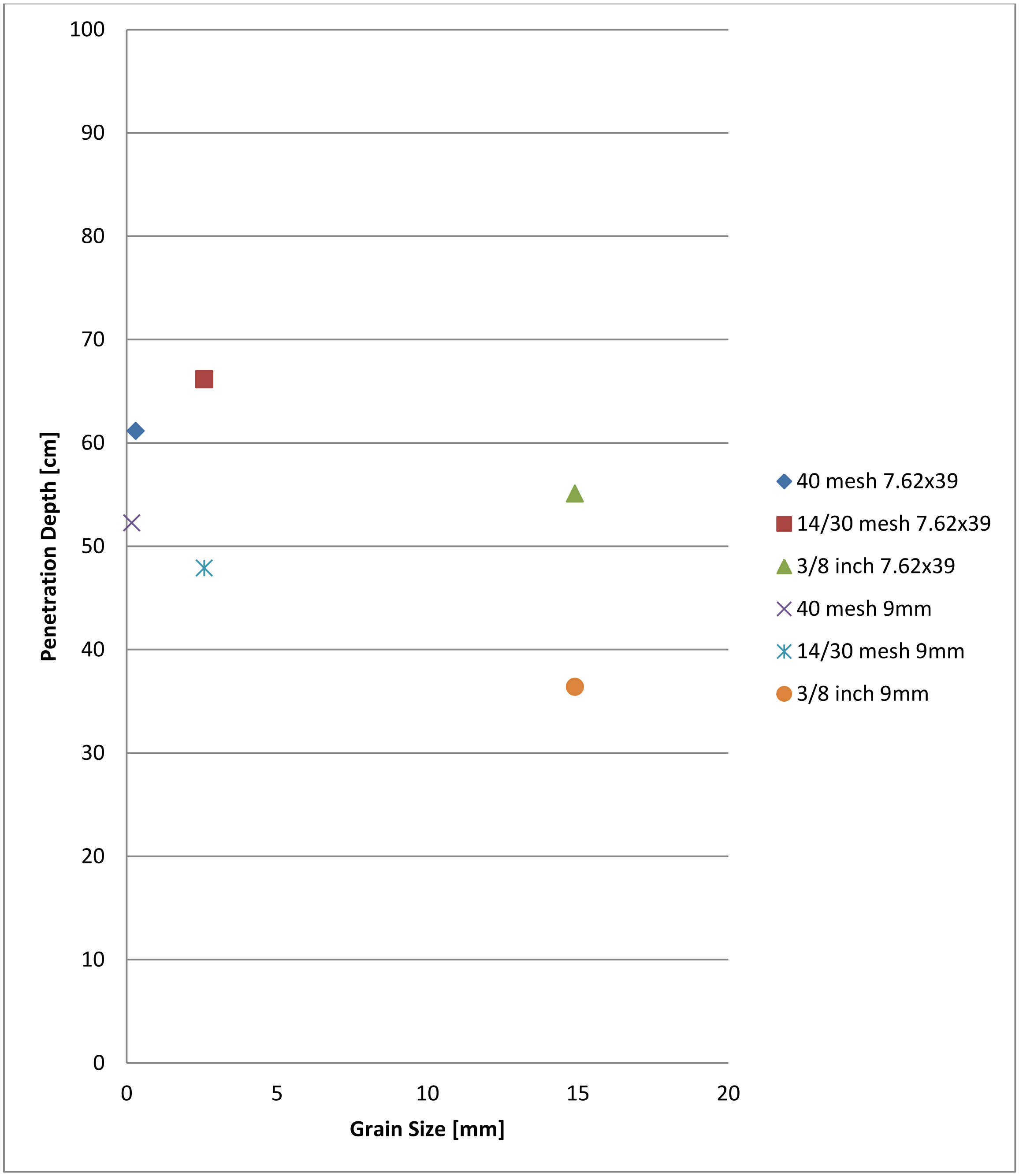


Figure 63 Average Penetration of Both Rounds vs. Average Grain Size of Rubber

In this case it is easy to see that the faster 7.62x39 round penetrated significantly deeper into the media than its 9mm counterpart. This could be due to the lack of deformation in both rounds or a totally different phenomenon related to the shear pressure as a function of velocity. This will be discussed further in Chapters 5 and 6.

There appears to be a greater dependence on the velocity for penetration into rubber as can be noticed in Figure 64 (shown below). Here, the projectile penetration is plotted versus projectile velocity.

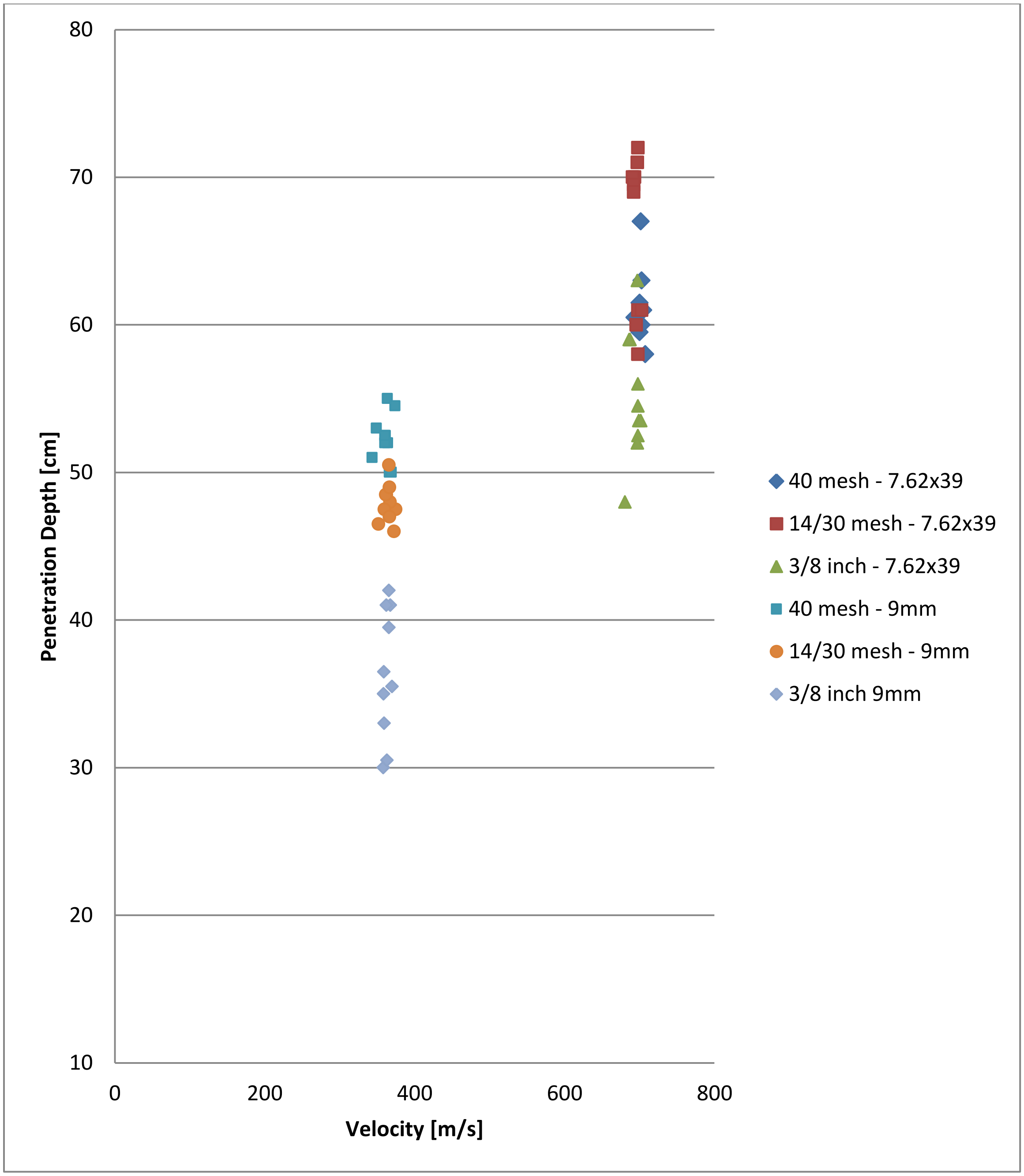


Figure 64 Penetration of Rubber vs. Velocity

There is clearly greater penetration in all rubbery media with the 7.62x39 round than there is with the 9mm round. This could be due to the shape/size of the two rounds, or the effect of velocity. It can be noticed that the 7.62x39 round travels at nearly twice the velocity of the 9mm round, but does not necessarily achieve twice the penetration.

Chapter 5: Discussion

There are several noticeable trends involving the penetration of the 9mm round, however the 7.62x39 round does not follow the same trends. In sand and rubber, the 9mm consistently shows reduction in penetration with increasing grain size, but the same is not necessarily true with the 7.62x39 round. One facet of the data that is consistent between the two rounds and media (sand and rubber) is that the largest of the grain sizes experiences the lowest average penetration. Another noticeable trend is the tendency of the 9mm round to penetrate deeper in sand on average (regardless of grain size) than the 7.62x39 round. This is independent of deformation in the finest sand (60/80 mesh) because in several shots, the 7.62x39 round had negligible deformation, and still penetrated less.

5.1 Effects of Varying Sand Grain Size

Understanding the overall effects of varying grain size is a complicated problem. In order to tackle this problem, the two rounds should be looked at independently.

5.1.1 The 7.62x39 Round

The effects of varying grain size of sand on the 7.62x39 round is of great importance because this particular round is used both with and against US military forces. The overall effect that is first noticed, when looking at the projectiles after impact, is that the round fragments more when fired at coarser sand. When the data is examined it becomes apparent that the round also manages to penetrate less in the coarser sand. This phenomenon could be understood through the effects of taking this to the extremes on both ends of the spectrum. For instance, if the grains are enlarged to the point that the projectile is, in effect, impacting a solid rock surface, the penetration will be considerably less if there is penetration at all. On the other hand, if the grain size is decreased to the point that the granular matter is basically single molecules, there will be no crushing of grains (totally eliminating one mechanism that aids in stopping the projectile), and also creating a less uniform packing order (hence reducing effective density), which acts to reduce the pressure that stops the bullet, and therefore causes an increase in the penetration depth. With that said, the opposite ends of the spectrum clearly point to a decrease in penetration with an increase in grain size. The problem found in the data is that for the samples tested, an intermediate grain size showed the highest penetration, not the finest but rather the second finest.

5.1.1 The 9mm Round

The results are more conclusive with the 9mm round than with the 7.62x39 round which could be due to many reasons. There is said to exist for a given granular material, a critical velocity, above and below this velocity, projectiles will experience less penetration. Since the 9mm is far slower than its counterpart, this could be a sign that the critical velocity lies somewhere between, or even at a slower velocity than the 9mm travels. One thing that is noticeable that relates directly to this study is the effect that varying the grain size has on the penetration of the 9mm round. For every increase in grain size there is a direct decrease in the average penetration into the respective media (see Figure 65 below).

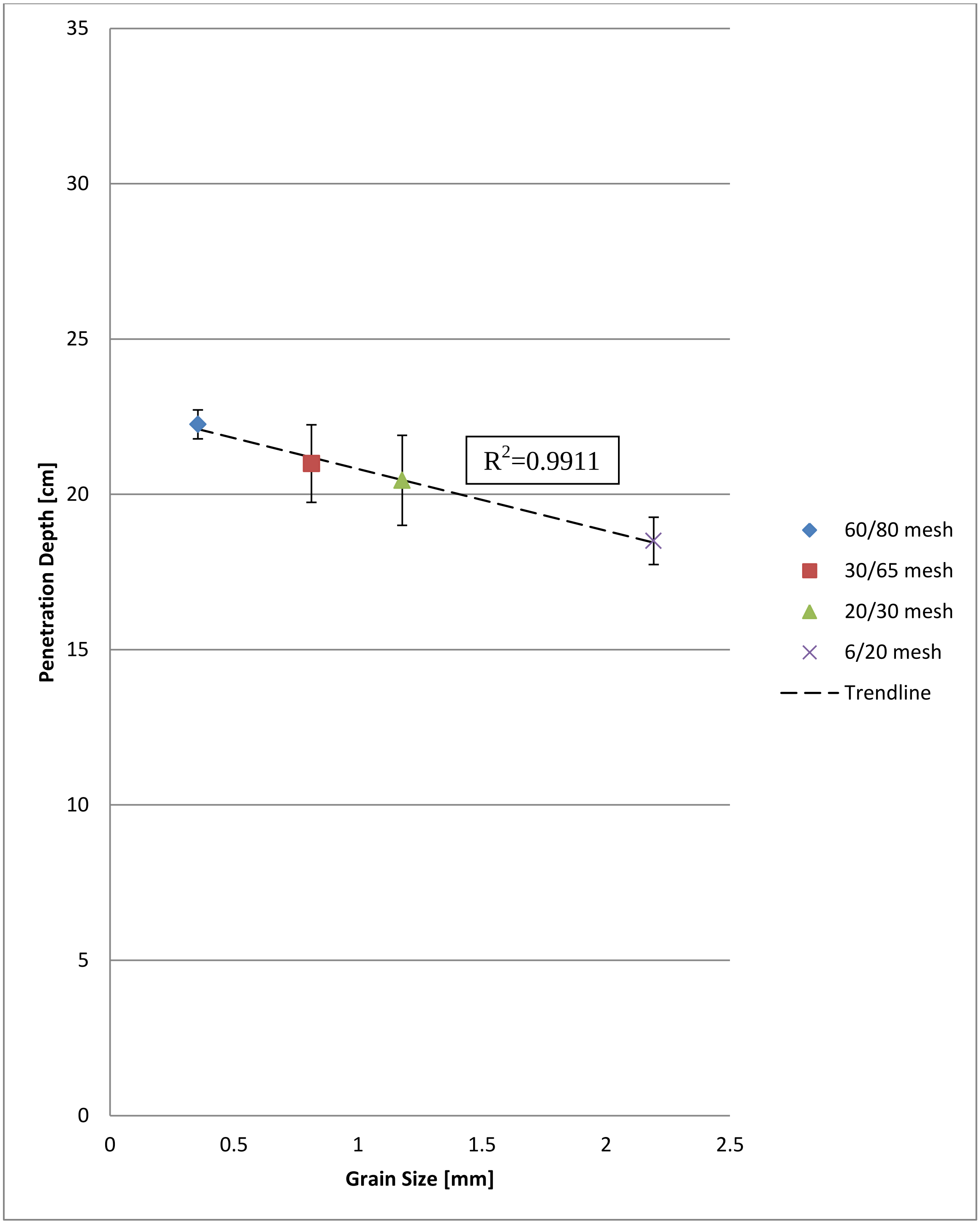


Figure 65 Average Penetration of 9mm Round vs. Average Grain Size

This graph shows (for the grain sizes, and over the range of sizes, tested) a nearly linear relationship between the grain size and average penetration depth.

5.2 Effects of Varying Rubber Grain Size

Varying grain size in rubber has similar effects to those found in sand. The reaction of the 7.62x39 was to penetrate deeper into an intermediate grain size. The largest grain sizes had the smallest penetrations of all tested. However, unlike sand, the rubber was penetrated deeper by the 7.62x39 round than the slower 9mm round. In the 3/8 inch rubber the bullets tended to get deflected and travel up or down into adjacent bags. This proved difficult to test the penetration, as many tests were not measurable.

5.2.1 The 7.62x39 Round

One interesting note on the reaction of the 7.62x39 round was its ability to, on occasion, break into the third bag. As previously stated, the 14/30 mesh rubber and 7.62x39 combination produced consistent results with penetration either at around 60 cm or around 70 cm, but not really in between (as depicted in Figure 66 below). This was noticed during testing as well. Many shots into the 40 and 14/30 mesh rubbers ended with the bullet resting at the very end of the second sandbag which is around 60 cm. With the 14/30 mesh, on occasion, the bullet would penetrate the third bag, except, instead of stopping just past 60 cm, the bullet would penetrate much deeper. This gives a clue to the effects of using the woven polypropylene sandbag as a method for containing crumb rubber.

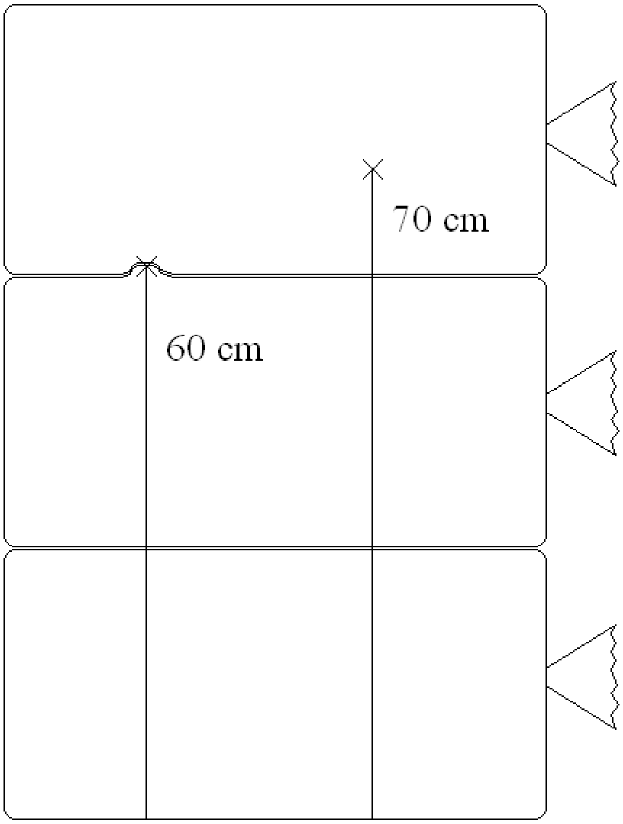


Figure 66 Effect of Double Sandbag Interface on Penetration

5.2.2 The 9mm Round

The 9mm round proved to give the most consistent results in terms of average penetration. There is a clear trend across the range of granulated rubber tested that points to larger chunks as being the most efficient at stopping the 9mm bullets.

5.3 Impact Cratering, Granular Jets, and Buckling/Phase Transition Effects

No granular jets were filmed during this experimentation, and due to the design of the redoubt, the oncoming bullets left no clear craters, however impact did cause an impression in the side of each sandbag which proved to have more prominence in the coarser sand, namely the 6/20 mesh. In some cases, the bag suffered what was deemed "trauma", and the bag was blown somewhat outward. Below, Figure 67 is a picture of a bag that showed this effect.

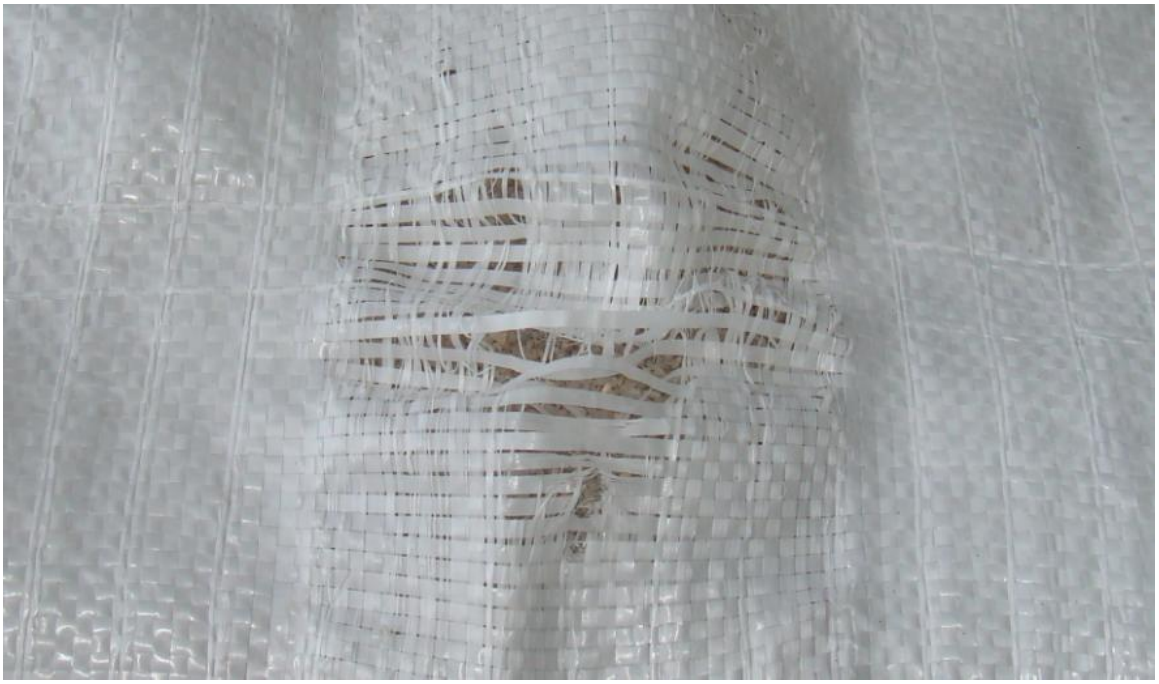


Figure 67 Trauma to Bags

The presence of the trauma was not present in the bags that contained the finer sands, the rubber materials and was not present with the use of the 9mm round.

As for Buckling and phase transition, the effects on the projectiles is shown in the drastically fragmented 7.62x39 rounds in the preceding Figures 39 and 61. The 9mm round did not suffer extreme deformation, but did show signs of wear on one side.

5.4 Tumbling

It was recorded that the position of the round at its final resting point in the bag was often sideways or backwards. In the case of the 9mm and in some of the least damaged 7.62x39 rounds, it was noticed that one side had greater wear. This could be due to the worn side being on the leading edge after initial penetration during the period from straight entry to sideways or backwards resting position. The position of the bullet as it passed through multiple bags, in the case of the rubber, can be noted upon as being sideways in many cases. The bullets would often leave a large hole as they traveled from one bag to another. It seems this is due to the orientation of the projectiles as they passed through the bags.

5.5 Influence of Size/Shape

The effects of varying size and shape were not noticeable because the projectiles that differed in shape also differed in velocity. In the case of the sand it seemed that the velocity played a far greater role than the shape and size because the 7.62x39 projectiles are 7.62 mm in diameter and the 9mm projectiles are 9 mm in diameter, also the 7.62x39 projectiles are more conically shaped than the round-ended 9mm rounds. Together, the size and shape of the 7.62x39 seem better for penetration, yet the penetration was noticeably less in most cases. Again, it is hard to base conclusions upon this because of the variance in velocity, but it can be said that the change in shape did not have as much effect as the change in velocity. It appears that increasing velocity causes the sand to "thicken" or increase its shear resistance to penetration. The phenomenon of shear thickening is referred to, for fluids, as being dilatant.

5.6 Crushing of Sand Grains

There was a noticeable amount of white powder present in the bags near the path of the bullet after each shot (shown in Figure 68 below). This was more prevalent in the larger sizes of sand, and since the 7.62x39 rounds were tested first and suffered greater wear and fragmentation in the larger sizes of sand, it was originally thought that this white powder could be lead dust. After tests began with the 9mm, it was noticed that the white powder was still present. With the condition of the 9mm rounds being whole and still fully-jacketed, the assumption of lead powder being a possible answer was proved not probable. Instead, it is thought to be a sign of the crushing of grains that occurs in sand impacts.

Figure 68 White Powder Found in Target Bags Post-Impact

This white powder lead from the entry point to the bullet, and actually served as an indicator to the path the projectiles traveled through the media.

Chapter 6: Conclusions

The most conclusive effects of varying grain size are found with the use of the 9mm caliber. There are other mechanisms such as fragmentation and deformation that directly impact penetration performance in the case of the 7.62x39 into sand, and these effects change with grain size, but for this reason the 7.62x39 proved to have unintended results and therefore unintended conclusions.

6.1 The 7.62x39 Round

The 7.62x39 round travels at approximately 700 m/s when fired through the AR-15, and has the potential for causing great damage to anything downrange. For that reason, it is important to find out how to best stop it, and what characteristics should be considered when constructing a redoubt to do so.

6.1.1 Sand

It is important to consider all aspects when using sand to stop projectiles. One aspect is the ability for the material to “hourglass” its way out of the bag through the point of entry for the projectile. It was found that with larger grains of sand, the hourglass effect was attenuated by the larger grains. As the grains’ size became closer to the size of the hole the projectile entered the bag through, they did not move as freely through the hole, and therefore more sand stayed in the pile overall. However, in some tests with the larger grains the trauma to the bag caused larger openings for the sand to escape.

A fairly noticeable conclusion is that the finer sand tends to leave the bullet less deformed and in one piece, and therefore if the goal is to mitigate heavy metals from leaching into groundwater at outdoor shooting ranges that utilize sand as a bullet trap, fine grained sand should be used rather than coarse sand. In using sand as a barrier for stopping bullets, it can be stated that very coarse sand (>2 mm grains) prevents penetration better than fine sand in the case of a single shot. However, multiple shots could have a wearing effect on the sand making it inherently smaller with every shot.

6.1.2 Rubber

In shooting the 7.62x39 round into sandbags filled with rubber, the thickness and order of the sandbags can affect the overall penetration, because, as stated in Chapter 5, the bag can be a tough barrier to break through, even when the projectile has the potential for penetrating much further. If the sandbag was not used to contain the rubber, greater penetration would have occurred, and therefore, the boundary conditions are of great importance when modeling impact of solid projectiles on crumb-rubber targets especially in terms of the flexibility and toughness of the container.

6.2 The 9mm Round

The 9mm round used in experimentation traveled at a velocity of approximately 360 m/s, and proved to have different reactions to both targets than the 7.62x39 round. The data on the 9mm shots contains trends that are hard to ignore, and are actually desirable when making generalizations about the effects of varying the grain size of the media on penetration depth. With every increase of grain size, a decrease in penetration is observed. The 9mm round stayed in-tact in all experiments. Tumbling of the round was observed in all media.

6.2.1 Sand

Under impact with the sand, the 9mm round showed slight wearing of one side, and with every increase of grain size, the round, showed slightly larger indentations on the tip. Decreasing penetration depth was shown to correlate with increasing the grain size of the sand. This was not the case with the 7.62x39 round, but also differed in the lack of deformation.

6.2.2 Rubber

The 9mm round showed similar results in rubber as were observed in sand. The penetration decreased with every increase in grain size; however, the number of different rubber grain sizes tested is lower than that used in the sand experiments.

6.3 Overall Conclusions

- Projectile penetration into granular media is significantly dependent on the grain size of the media
- The 9mm penetration data shows a strong linear relationship between grain size and penetration depth (decreasing penetration with increasing grain size) in both materials
- Sand is better than rubber for stopping bullets in the shortest distance
- Pistol and rifle penetration in sand are nearly equal
- The 7.62x39 projectile travels at a velocity approximately 93% greater than that of the 9mm
- 7.62x39 projectile penetration in rubber is approximately 33% greater than that of the 9mm
- Fine sand causes less deformation and fragmentation of the projectiles than coarse

- Fine sand is better for preventing unwanted heavy metal leachate into groundwater at outdoor firing ranges that utilize sand as a bullet trap
- Coarse sand allows the least amount of penetration for either round
- Coarse rubber allows the least amount of penetration for either round
- Rubber causes little to no deformation or wear on the projectiles making it better suited for firing ranges that recycle spent ammunition
- Pound for pound, sand is better for stopping 7.62x39 rounds (coarse sand being the absolute best)
- Pound for pound, rubber is better for stopping 9mm rounds (coarse rubber being the absolute best)
- The bag suffers more trauma when coarse sand is used rather than fine sand

The best media to use in a given situation depends on the characteristics that are most important to the user. If the least possible penetration is of greatest importance, coarse sand is the best choice. If keeping the rounds intact, therefore preventing environmental contamination is of importance, fine sand or rubber is best. Whenever possible, firing range operators should implement recycled tire material in their bullet traps for this reason. For military applications, it is necessary to utilize a fire-retardant with crumb rubber to prevent the barrier from igniting and releasing noxious gases. Rubber can be used in military applications under certain circumstances, but it is necessary to compensate for the increase in penetration when compared with sand.

One fact noted previously is that wet sand is less effective at preventing penetration than dry sand [12, 19, and 20]. It is reasonable to question whether this would be the case for rubber as well, or that rubber might show a reverse trend and get better with increasing moisture levels. Also, it is possible that rubber might shed water better than sand and preserve itself as a lighter, more easily movable barrier.

In conclusion, it appears that the initial hypothesis of decreasing penetration depth with increasing grain size is fairly accurate when considering a large difference of grain sizes.

Chapter 7: Future Work

In order to better understand the phenomenon recorded in the present study, the effects of several variables need to be studied further. It is understood that moisture content directly reduces, in certain cases, the penetration of a projectile into sandy media. However, the questions remain of what the significance of moisture content is with varying grain size and how varying projectile velocity effects penetration as well.

7.1 Varying Moisture Content

Does moisture have less of an effect on coarse sand than it does on fine sand? If so, how much of an effect does it have? This can be answered through a series of similar tests in which water is introduced in varying amounts, or added liberally to the point of total saturation. The problem lies in appropriately defining what moisture levels can and should be tested, because as this work deals with relatively only one moisture content (dry), an experiment of varying moisture content would clearly eclipse this work in scope. Many tests need to be performed on all various sizes for each level of moisture, and therefore the number of tests is multiplied by each degree of moisture tested. It might be appropriate to test fully saturated sand and at least one intermediate moisture level, as might exist on the battlefield. This might entail just leaving a sprinkler on the sand overnight to simulate a rainstorm and letting it dry for a day or two. In this case, the sand will have time to allow excess water to escape, while still maintaining a significant moisture level.

7.2 Varying Projectile Velocity

It is clear, in the present study, that projectile velocity plays a significant role in penetration depth into sandy media. It becomes easy to speculate, that a slower 7.62 mm projectile might achieve more penetration than the ones tested. Further testing of the same projectile at different velocities might give insight of the critical velocity at which the projectile achieves the greatest penetration. It is necessary to have ample data of penetration at many different velocities such that conclusions can be reached with respect to velocity dependent penetration in the various media.

It is, again, clear that the breadth of testing necessary to fully classify any given impact of a projectile and granular material is very large. The number of tests needed to determine the effects of all variables involved becomes exponentially greater than those of the present work. However, if there is enough data at discrete levels of velocity and moisture, then trends can be formed and functions can be attained involving velocity, moisture and grain size. This would be a great improvement over the simplified penetration equations that are merely quadratic functions of velocity with coefficients dependent on grain size and moisture content that must be determined for every different combination.

7.3 Computer Based Modeling and Simulation

There are possibilities of modeling the granulate materials as solid viscoelastic continuum instead of modeling the individual grains, but in order to do so, more study is necessary in determining the plastoelastic properties of various grain sizes at various moisture levels especially at high strain rates.

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Appendices

Appendix A: Experimental Data

Table A Experimental Data

	60/80 mesh	7.62x39			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	Notes
1	18.2	2263	689.7624	0.7	slight deformation; 9-25-10, 1:00-3:00pm, 93° F, 53% humidity
2	18.8	2298	700.4304	0.8	slight deformation
3	20	2294	699.2112	0.9	slight deformation
4	22.4	2298	700.4304	0.9	
5	13	2290	697.992	0.8	curved over ~ 11.5 cm
6	21	2314	705.3072	0.6	deformation; 9-26-10, 2:30-3:55pm, 94° F, 45% humidity
7	19	2219	676.3512	0.6	brass and lead seperated
8	20.2	2287	697.0776	0.6	slight deformation
9	22.5	2306	702.8688	0.6	slight deformation
10	19.6	2318	706.5264	0.6	medium deformation
	19.47	2288.7	697.59576		
	30/65 mesh	7.62x39			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	20.2	2335	711.708	0.6	slight deformation; 9-26-10, 4:00-4:55pm, 92.5° F, 49% humidity
2	24.8	2310	704.088	0.5	slight deformation
3	21	2314	705.3072	0.5	significant deformation
4	22.3	2322	707.7456	0.5	medium deformation
5	20	2322	707.7456	0.5	severe deformation
6	19.7	2322	707.7456	0.5	severe deformation
7	18	2306	702.8688	0.5	fragmentation (5 pieces)
8	19	2312	704.6976	0.5	severe deformation
9	18	2339	712.9272	0.5	fragmentation and severe deformation (4 pieces)
10	27	2279	694.6392	0.5	significant deformation mushroom
	21	2316.1	705.94728		
	20/30 mesh	7.62x39			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	17	2275	693.42	0.5	fragmentation; 9-26-10, 5:00-5:40pm, 88° F, 56% humidity
2	16	2306	702.8688	0.5	severe deformation and slight fragmentation
3	16.3	2287	697.0776	0.5	severe deformation and slight fragmentation
4	21.5	2279	694.6392	0.5	abnormal trauma to bag, bellying above entry point, severe deformation and fragmentation
5	17.4	2326	708.9648	0.5	bellying up of top of bag, severe deformation and fragmentation
6	18.5	2298	700.4304	0.5	bellying up of top of bag, severe deformation and fragmentation
7	17.3	2298	700.4304	0.5	bellying up of top of bag, severe deformation and fragmentation
8	18.2	2294	699.2112	0.5	bellying up of top of bag, severe deformation and fragmentation (large fragments
9	16.1	2298	700.4304	0.5	bellying up of top of bag, severe deformation
10	18.7	2318	706.5264	0.5	severe trauma to bag at entry point
	17.7	2297.9	700.39992		
	6/20 mesh	7.62x39			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	18.6	2318	706.5264	0.5	severe deformation and fragmentation; 9-26-10, 5:40-6:10 pm, 88° F, 56% humidity
2	17.2	2306	702.8688	0.5	severe trauma to bag at entry point and severe fragmentation
3	21	2298	700.4304	0.5	trauma to bag, severe fragmentation
4	16.1	2248	685.1904	0.5	fragmentation
5	22.5	2310	704.088	0.6	trauma to bag, bullet curved up slightly; 9-28-10, 9:30-10:30 am, 88.5° F, 62% humidity
6	15.1	2310	704.088	0.6	very little trauma to bag, fragments near entry point
7	17.2	2314	705.3072	0.6	no trauma to bag bellying up of top of bag
8	15.4	2279	694.6392	0.6	no trauma to bag bellying up of top of bag
9	16.1	2252	686.4096	0.6	no trauma to bag bellying up of top of bag
10	16.5	2302	701.6496	0.6	no trauma to bag bellying up of top of bag
	17.57	2293.7	699.11976		

Appendix A: (Continued)

Table A (Continued)

	40 mesh	7.62x39			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	67	2302	701.6496	0.7	bullet facing backwards, 3rd bag; 9-28-10, 10:30-1:30 pm, 89.6° F, 62% humidity
2	61	2310	704.088	0.7	bullet facing backwards, 2nd bag
3	58	2322	707.7456	0.7	bullet facing backwards, 2nd bag
4	60	2302	701.6496	0.7	bullet sideways, 2nd bag
5	60.5	2275	693.42	0.7	bullet sideways, 2nd bag
6	61.5	2298	700.4304	0.7	bullet sideways, 2nd bag
7	61	2314	705.3072	0.7	bullet sideways, 2nd bag
8	59.5	2298	700.4304	0.7	bullet sideways, 2nd bag
9	63	2306	702.8688	0.7	bullet sideways, 3rd bag
10	60	2306	702.8688	0.7	bullet sideways, 2nd bag
	61.15	2303.3	702.04584		
	14/30 mesh	7.62x39			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	61	2290	697.992	0.7	bullet sideways, 2nd bag; 9-28-10, 1:30-3:00 pm, 91.2° F, 60% humidity
2	70	2275	693.42	0.7	bullet sideways, 3rd bag
3	70	2267	690.9816	0.7	bullet sideways, 3rd bag
4	60	2283	695.8584	0.7	bullet sideways, 2nd bag
5	61	2306	702.8688	0.7	bullet straight, 2nd bag
6	58	2290	697.992	0.7	bullet sideways, 2nd bag
7	69.5	2271	692.2008	0.7	bullet facing backwards, 3rd bag
8	71	2287	697.0776	0.7	bullet sideways, 3rd bag
9	72	2290	697.992	0.7	bullet sideways, 3rd bag
10	69	2271	692.2008	0.7	bullet facing backwards, 3rd bag
	66.15	2283	695.8584		
	3/8 inch	7.62x39			
Trial #	Penetration Depth	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	53.5	2294	699.2112	0.7	bullet straight, 2nd bag; 9-29-10, 3:00-5:00 pm, 90.3° F, 53% humidity
2	56	2290	697.992	0.7	bullet sideways, 2nd bag
3	52.5	2290	697.992	0.7	bullet sideways, 2nd bag
4	53.5	2302	701.6496	0.7	bullet sideways, 2nd bag
5	59	2256	687.6288	0.7	bullet facing backwards, 10-1-10, 3:30-4:50pm, 99.5° F, 31% humidity
6	59	2252	686.4096	0.7	bullet facing backwards, 2nd bag
7	52	2287	697.0776	0.7	bullet facing backwards, 2nd bag
8	54.5	2290	697.992	0.7	bullet facing backwards, 2nd bag
9	63	2287	697.0776	0.7	bullet facing backwards, 2nd bag
10	48	2233	680.6184	0.7	bullet facing backwards, 2nd bag
	55.1	2278.1	694.36488		

Appendix A: (Continued)

Table A (Continued)

	60/80 mesh	9mm			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	22.5	1183	360.5784	0.6	1st bag, bellying up of top of bag 10-2-10, 1:00-1:50pm, 91.4° F, 34% humidity
2	22.5	1208	368.1984	0.6	1st bag, bellying up of top of bag
3	23.5	1187	361.7976	0.6	1st bag, bellying up of top of bag
4	22.5	1174	357.8352	0.6	1st bag, bellying up of top of bag
5	22	1185	361.188	0.6	1st bag, bellying up of top of bag
6	22	1216	370.6368	0.6	1st bag, bellying up of top of bag
7	23	1199	365.4552	0.6	1st bag, bellying up of top of bag
8	21.5	1172	357.2256	0.6	1st bag, bellying up of top of bag
9	21.5	1178	359.0544	0.6	1st bag, bellying up of top of bag
10	21.5	1164	354.7872	0.6	1st bag, bellying up of top of bag
	22.25	1186.6	361.67568		

	30/65 mesh	9mm			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	21.5	1163	354.4824	0.5	1st bag, bellying up of top of bag 10-2-10, 1:50-2:30pm, 91.4° F, 34% humidity
2	20.5	1202	366.3696	0.5	1st bag
3	25	1175	358.14	0.5	1st bag, hit high on bag, rode top of bag
4	20.5	1178	359.0544	0.5	1st bag
5	20.5	1203	366.6744	0.5	1st bag
6	23	1189	362.4072	0.5	1st bag, bellying up of top of bag
7	19.9	1161	353.8728	0.5	1st bag, bellying up of top of bag
8	20	1191	363.0168	0.5	1st bag
9	18.5	1170	356.616	0.5	1st bag
10	20.5	1191	363.0168	0.5	1st bag, bellying up of top of bag
	20.99	1182.3	360.36504		

	20/30 mesh	9mm			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	19	1175	358.14	0.5	1st bag, bellying of top of bag, 10-2-10, 2:30-3:00 pm, 92.5° F, 35% humidity
2	18.5	1163	354.4824	0.5	1st bag
3	25	1183	360.5784	0.5	1st bag, bellying of top of bag, rode top of bag
4	21.5	1175	358.14	0.5	1st bag, bellying of top of bag
5	19	1187	361.7976	0.5	1st bag
6	18.5	1194	363.9312	0.5	1st bag
7	22.5	1205	367.284	0.5	1st bag, bellying of top of bag
8	20.5	1188	362.1024	0.5	1st bag, bellying of top of bag
9	19	1159	353.2632	0.5	1st bag
10	21	1187	361.7976	0.5	1st bag, bellying of top of bag
	20.45	1181.6	360.15168		

	6/20 mesh	9mm			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	17.5	1183	360.5784	0.6	1st bag, bellying up of top of bag 10-2-10, 3:20-4:15pm, 91.4° F, 34% humidity
2	17.5	1179	359.3592	0.6	1st bag, bellying up of top of bag
3	18.5	1195	364.236	0.6	1st bag, bellying up of top of bag
4	20	1201	366.0648	0.6	1st bag, bellying up of top of bag
5	19.5	1162	354.1776	0.6	1st bag, bellying up of top of bag
6	19	1191	363.0168	0.6	1st bag, bellying up of top of bag
7	20	1186	361.4928	0.6	1st bag, bellying up of top of bag
8	18.5	1174	357.8352	0.6	1st bag, bellying up of top of bag
9	17	1143	348.3864	0.6	1st bag, bellying up of top of bag
10	17.5	1180	359.664	0.6	1st bag, bellying up of top of bag
	18.5	1179.4	359.48112		

Appendix A: (Continued)

Table A (Continued)

	40 mesh	9mm			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	53	1145	348.996	0.5	bullet sideways, 2nd bag 10-1-10, 3:30-4:50pm, 99.5° F, 31% humidity
2	52	1195	364.236	0.5	bullet sideways, 2nd bag
3	55	1194	363.9312	0.5	bullet sideways, 2nd bag
4	52	1183	360.5784	0.5	bullet sideways, 2nd bag
5	54.5	1227	373.9896	0.5	bullet sideways, 2nd bag
6	51	1127	343.5096	0.5	bullet facing backwards, 2nd bag
7	52.5	1185	361.188	0.5	bullet sideways, 2nd bag, 10-2-10, 8:45-9:30, 81.7° F, 60% humidity
8	50	1203	366.6744	0.5	bullet sideways, 2nd bag
9	50	1211	369.1128	0.5	bullet facing backwards, 2nd bag
10	52.5	1183	360.5784	0.5	bullet facing backwards, 2nd bag
	52.25	1185.3	361.27944		
	14/30 mesh	9mm			
Trial #	Penetration Depth [cm]	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	47.5	1230	374.904	0.5	bullet sideways, 2nd bag 10-2-10, 9:30-10:30pm, 81.7° F, 60% humidity
2	46	1222	372.4656	0.5	bullet sideways, 2nd bag
3	48.5	1189	362.4072	0.5	bullet sideways, 2nd bag
4	48	1205	367.284	0.5	bullet sideways, 2nd bag
5	50.5	1200	365.76	0.5	bullet sideways, 2nd bag
6	47.5	1180	359.664	0.5	bullet sideways, 2nd bag
7	48.5	1186	361.4928	0.5	bullet sideways, 2nd bag
8	47	1202	366.3696	0.5	bullet sideways, 2nd bag
9	46.5	1154	351.7392	0.5	bullet sideways, 2nd bag
10	49	1203	366.6744	0.5	bullet sideways, 2nd bag
	47.9	1197.1	364.87608		
	3/8 inch	9mm			
Trial #	Penetration Depth	Velocity [ft/s]	Velocity [m/s]	Moisture	
1	33	1179	359.3592	0.7	2nd bag, 10-2-10, 10:30-12:00am, 81.7° F, 60% humidity
2	42	1200	365.76	0.7	2nd bag
3	39.5	1200	365.76	0.7	2nd bag
4	30	1175	358.14	0.7	1st bag
5	30.5	1191	363.0168	0.7	1st bag
6	35	1176	358.4448	0.7	2nd bag, deflectled upward
7	41	1206	367.5888	0.7	2nd bag
8	41	1189	362.4072	0.7	2nd bag
9	36.5	1178	359.0544	0.7	2nd bag
10	35.5	1213	369.7224	0.7	2nd bag
	36.4	1190.7	362.92536		

Appendix B: Major Dimension Grain Measurements

Table B Measured Grain Sizes

	Sand					Rubber		
#	60/80	30/65	20/30	6|20		40 mesh	14-30	3/8"
1	0.148	0.575	0.708	1.390		0.019	1.09	9.14
2	0.172	0.596	0.822	1.550		0.030	1.40	9.41
3	0.204	0.640	0.837	1.550		0.043	1.55	9.64
4	0.206	0.679	0.914	1.585		0.044	1.69	9.74
5	0.214	0.690	0.961	1.715		0.050	1.92	10.74
6	0.216	0.695	0.968	1.720		0.069	2.00	10.99
7	0.217	0.724	0.997	1.785		0.070	2.05	11.16
8	0.225	0.730	1.030	1.800		0.076	2.06	13.08
9	0.231	0.735	1.047	1.920		0.081	2.10	13.15
10	0.232	0.764	1.051	1.995		0.103	2.11	13.20
11	0.233	0.772	1.077	2.015		0.108	2.39	14.13
12	0.236	0.776	1.098	2.030		0.113	2.40	14.58
13	0.237	0.788	1.107	2.090		0.115	2.41	15.14
14	0.245	0.796	1.124	2.090		0.118	2.42	15.16
15	0.252	0.802	1.132	2.125		0.119	2.43	15.21
16	0.255	0.804	1.148	2.145		0.130	2.54	15.34
17	0.258	0.835	1.150	2.205		0.135	2.55	15.72
18	0.258	0.861	1.157	2.280		0.141	2.65	16.05
19	0.261	0.865	1.173	2.290		0.145	2.82	16.15
20	0.264	0.869	1.173	2.305		0.152	2.84	16.20
21	0.279	0.885	1.220	2.340		0.155	2.86	16.35
22	0.281	0.905	1.259	2.390		0.157	3.02	16.45
23	0.286	0.923	1.269	2.415		0.160	3.03	16.55
24	0.286	0.940	1.307	2.440		0.162	3.09	16.73
25	0.288	0.947	1.340	2.450		0.177	3.16	16.96
26	0.288	0.949	1.554	2.520		0.186	3.38	17.55
27	0.293	0.952	1.565	2.670		0.186	3.50	17.89
28	0.295	0.953	1.706	2.915		0.191	3.59	19.78
29	0.296	0.965	1.727	3.070		0.192	4.15	21.65
30	0.302	0.966	1.731	3.975		0.194	4.30	23.22
31	0.302					0.202		
32	0.309					0.203		
33	0.309					0.205		
34	0.311					0.208		
35	0.313					0.215		

Appendix B: (Continued)

Table B (Continued)

	Sand					Rubber		
#	60/80	30/65	20/30	6|20		40 mesh	14-30	3/8"
36	0.314					0.223		
37	0.314					0.225		
38	0.318					0.226		
39	0.320					0.228		
40	0.320					0.228		
41	0.320					0.229		
42	0.322					0.232		
43	0.323					0.238		
44	0.324					0.261		
45	0.325					0.270		
46	0.336					0.273		
47	0.338					0.281		
48	0.338					0.282		
49	0.341					0.283		
50	0.349					0.284		
51	0.352					0.303		
52	0.353					0.310		
53	0.354					0.315		
54	0.358					0.319		
55	0.359					0.321		
56	0.366					0.326		
57	0.372					0.327		
58	0.373					0.327		
59	0.381					0.327		
60	0.382					0.330		
61	0.382					0.335		
62	0.382					0.337		
63	0.385					0.338		
64	0.390					0.343		
65	0.390					0.368		
66	0.394					0.370		
67	0.395					0.373		
68	0.395					0.389		
69	0.396					0.394		
70	0.398					0.395		

Appendix B: (Continued)

Table B (Continued)

	Sand					Rubber		
#	60/80	30/65	20/30	6|20		40 mesh	14-30	3/8"
71	0.399					0.395		
72	0.406					0.398		
73	0.408					0.400		
74	0.408					0.400		
75	0.412					0.400		
76	0.413					0.403		
77	0.414					0.412		
78	0.418					0.413		
79	0.420					0.417		
80	0.420					0.424		
81	0.428					0.425		
82	0.429					0.428		
83	0.431					0.433		
84	0.432					0.436		
85	0.435					0.450		
86	0.438					0.451		
87	0.448					0.461		
88	0.451					0.464		
89	0.451					0.484		
90	0.458					0.493		
91	0.479					0.502		
92	0.486					0.530		
93	0.513					0.565		
94	0.515					0.595		
95	0.519					0.615		
96	0.537					0.643		
97	0.554					0.668		
98	0.566					0.757		
99	0.634					0.823		
100	0.680					0.970		
Average								
	0.3546	0.8127	1.1784	2.1923		0.3051	2.583	14.902
Standard Deviation								
	0.09736	0.114549	0.26118	0.52131		0.17603	0.75472	3.4700

Appendix C: Measured Projectile Masses

Table C Measured Projectile Masses

	Mass [g]	
#	7.62x39	9mm
1	8.007	7.513
2	8.053	7.462
3	7.998	7.457
4	8.012	7.403
5	8.008	7.417
6	7.981	7.490
7	8.023	7.449
8	7.935	7.492
9	8.010	7.468
10	7.967	7.476
Average	7.9994	7.4627
Std Dev	0.03227	0.03368
Mass [Grains]	123.45	115.17

Appendix D: ANOVA Results

Table D ANOVA Results for 7.62x39 Round into Sand

Source of Variation	Sum of Squares	d.f.	Mean Squares	F
between	79.39	3	26.46	4.317
error	220.7	36	6.131	
total	300.1	39		

The probability of this result, assuming the null hypothesis, is 0.011

Group A: 60/80 Mesh; Number of items= 10
13.0 18.2 18.8 19.0 19.6 20.0 20.2 21.0 22.4 22.5

Mean = 19.470
95% confidence interval for Mean: 17.88 thru 21.06
Standard Deviation = 2.69
High = 22.50 Low = 13.00
Median = 19.80
Average Absolute Deviation from Median = 1.75

Group B: 30/65 Mesh; Number of items= 10
18.0 18.0 19.0 19.7 20.0 20.2 21.0 22.3 24.8 27.0

Mean = 21.000
95% confidence interval for Mean: 19.41 thru 22.59
Standard Deviation = 2.93
High = 27.00 Low = 18.00
Median = 20.10
Average Absolute Deviation from Median = 2.06

Group C: 20/30 Mesh; Number of items= 10
16.0 16.1 16.3 17.0 17.3 17.4 18.2 18.5 18.7 21.5

Mean = 17.700
95% confidence interval for Mean: 16.11 thru 19.29
Standard Deviation = 1.65
High = 21.50 Low = 16.00
Median = 17.35
Average Absolute Deviation from Median = 1.16

Appendix D: (Continued)

Table D (Continued)

Group D: 6/20 Mesh; Number of items= 10
15.1 15.4 16.1 16.1 16.5 17.2 17.2 18.6 21.0 22.5

Mean = 17.570
95% confidence interval for Mean: 15.98 thru 19.16
Standard Deviation = 2.44
High = 22.50 Low = 15.10
Median = 16.85
Average Absolute Deviation from Median = 1.73

Table E ANOVA Results for 7.62x39 Round into Rubber

Source of Variation	Sum of Squares	d.f.	Mean Squares	F
between	612.4	2	306.2	17.10
error	483.5	27	17.91	
total	1096.	29		

The probability of this result, assuming the null hypothesis, is less than .0001

Group A: 40 Mesh; Number of items= 10
58.0 59.5 60.0 60.0 60.5 61.0 61.0 61.5 63.0 67.0

Mean = 61.150
95% confidence interval for Mean: 58.40 thru 63.90
Standard Deviation = 2.44
High = 67.00 Low = 58.00
Median = 60.75
Average Absolute Deviation from Median = 1.55

Group B: 14/30 Mesh; Number of items= 10
58.0 60.0 61.0 61.0 69.0 69.5 70.0 70.0 71.0 72.0

Mean = 66.150
95% confidence interval for Mean: 63.40 thru 68.90
Standard Deviation = 5.42
High = 72.00 Low = 58.00
Median = 69.25
Average Absolute Deviation from Median = 4.35

Appendix D: (Continued)

Table E (Continued)

Group C: 3/8 Inch; Number of items= 10
48.0 52.0 52.5 53.5 53.5 54.5 56.0 59.0 59.0 63.0

Mean = 55.100
95% confidence interval for Mean: 52.35 thru 57.85
Standard Deviation = 4.29
High = 63.00 Low = 48.00
Median = 54.00
Average Absolute Deviation from Median = 3.20

Table F ANOVA Results for 9mm Round into Sand

Source of Variation	Sum of Squares	d.f.	Mean Squares	F
between	72.96	3	24.32	10.29
error	85.06	36	2.363	
total	158.0	39		

The probability of this result, assuming the null hypothesis, is 0.000

Group A: 60/80 Mesh; Number of items= 10
21.5 21.5 21.5 22.0 22.0 22.5 22.5 22.5 23.0 23.5

Mean = 22.2
95% confidence interval for Mean: 21.26 thru 23.24
Standard Deviation = 0.677
Hi = 23.5 Low = 21.5
Median = 22.2
Average Absolute Deviation from Median = 0.550

Group B: 30/65 Mesh; Number of items= 10
18.5 19.9 20.0 20.5 20.5 20.5 20.5 21.5 23.0 25.0

Mean = 21.0
95% confidence interval for Mean: 20.00 thru 21.98
Standard Deviation = 1.82
Hi = 25.0 Low = 18.5
Median = 20.5
Average Absolute Deviation from Median = 1.11

Appendix D: (Continued)

Table F (Continued)

Group C: 20/30 Mesh; Number of items= 10
18.5 18.5 19.0 19.0 19.0 20.5 21.0 21.5 22.5 25.0

Mean = 20.4
95% confidence interval for Mean: 19.46 thru 21.44
Standard Deviation = 2.11
Hi = 25.0 Low = 18.5
Median = 19.8
Average Absolute Deviation from Median = 1.65

Group D: 6/20 Mesh; Number of items= 10
17.0 17.5 17.5 17.5 18.5 18.5 19.0 19.5 20.0 20.0

Mean = 18.5
95% confidence interval for Mean: 17.51 thru 19.49
Standard Deviation = 1.11
Hi = 20.0 Low = 17.0
Median = 18.5
Average Absolute Deviation from Median = 0.900

Table G ANOVA Results for 9mm Round into Rubber

Source of Variation	Sum of Squares	d.f.	Mean Squares	F
between	1341.	2	670.7	84.65
error	213.9	27	7.923	
total	1555.	29		

The probability of this result, assuming the null hypothesis, is less than .0001

Group A: 40 Mesh; Number of items= 10
50.0 50.0 51.0 52.0 52.0 52.5 52.5 53.0 54.5 55.0

Mean = 52.250
95% confidence interval for Mean: 50.42 thru 54.08
Standard Deviation = 1.67
High = 55.00 Low = 50.00
Median = 52.25
Average Absolute Deviation from Median = 1.25

Table G (Continued)

Group B: 14/30 Mesh; Number of items= 10
46.0 46.5 47.0 47.5 47.5 48.0 48.5 48.5 49.0 50.5

Mean = 47.900
95% confidence interval for Mean: 46.07 thru 49.73
Standard Deviation = 1.31
High = 50.50 Low = 46.00
Median = 47.75
Average Absolute Deviation from Median = 1.00

Group C: 3/8 Inch; Number of items= 10
30.0 30.5 33.0 35.0 35.5 36.5 39.5 41.0 41.0 42.0

Mean = 36.400
95% confidence interval for Mean: 34.57 thru 38.23
Standard Deviation = 4.39
High = 42.00 Low = 30.00
Median = 36.00
Average Absolute Deviation from Median = 3.60

Appendix E: T-Test Results

Table H T-Test Results

			T-Test				
			Sand				
Projectile:	7.62x39				9mm		
	60/80 to 30/65				60/80 to 30/65		
	0.119951583				0.031710761		
	60/80 to 20/30	30/65 to 20/30			60/80 to 20/30	30/65 to 20/30	
	0.048197337	0.003863114			0.013307922	0.27398999	
	60/80 to 6/20	30/65 to 6/20	20/30 to 6/20		60/80 to 6/20	30/65 to 6/20	20/30 to 6/20
	0.057809268	0.005538498	0.445409723		8.32718E-08	0.001079574	0.011013711
			Rubber				
Projectile:	7.62x39				9mm		
	40 to 13/40				40 to 13/40		
	0.010055475				2.79784E-06		
	40 to 3/8	14/30 to 3/8			40 to 3/8	14/30 to 3/8	
	0.000815632	4.78441E-05			1.24288E-07	4.44592E-06	

Appendix F: Moisture Meter Calibration

Table I Moisture Meter Calibration

	Moisture Meter Calibration					
	60/80 Mesh	30/65 Mesh	20/30 Mesh	6/20 Mesh	Time	Oven Temp [°F]
Moisture Meter Reading [0-10]	0.8	0.8	0.8	0.8	8:25 PM	Put into Oven
Measured Mass [g]	600	600	600	600		250
Moisture Meter Reading [0-10]	0.7	0.7	0.7	0.7	9:00 PM	Temperature increased
Measured Mass [g]	599.7	599.9	599.5	599.9		300
					9:15 PM	Temperature increased
						350
Moisture Meter Reading [0-10]	0.7	0.7	0.7	0.7	9:40 PM	Out of Oven
Measured Mass [g]	599.5	599.7	599.5	599.7		
Moisture Meter Reading [0-10]	0.7	0.7	0.7	0.7	10:20 PM	
Measured Mass [g]	599.5	599.7	599.5	599.7		

About the Author

Robert Paul Cole is a mechanical engineering student at the University of South Florida in the College of Engineering. His educational interests include: mechanics, heat transfer, and so-called “green technologies”. Robert has lived and worked in Florida for most of his life. He graduated from Pasco High School (just north of USF) and after meeting the entrance requirements began work in the College of Engineering. After his first semester he then transferred to Dodge City Community College in Ford County, Kansas, where he played college football and continued to take as many engineering courses as possible (Dodge City Community College did not have an engineering school) until 2006 when he transferred back to USF to the College of Engineering. He has fulfilled all coursework requirements for both the B.S. and M.S. in Mechanical Engineering, and anticipates becoming a professional engineer by 2014.