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# Penetration Resistance of Concrete - A Review

Law Enforcement Equipment Technology

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## ACKNOWLEDGMENTS

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# Penetration Resistance of Concrete - A Review



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## FOREWORD

The Defense Nuclear Agency (DNA) is engaged in a continuing effort to enhance the security of nuclear weapons storage. In this effort, it is receiving technical support from the National Bureau of Standards' Law Enforcement Standards Laboratory (LESL), whose overall program involves the application of science and technology to the problems of crime prevention, law enforcement, and criminal justice.

LESL is assisting DNA's physical security program with support in the chemical science and the ballistic materials areas, among others.

Among the tasks being performed by LESL for DNA are the preparation and publication of several series of technical reports on the results of its researches. This document is one such report.

Technical comments and suggestions are invited from all interested parties. They may be addressed to the author, or the Law Enforcement Standards Laboratory, National Bureau of Standards, Washington, DC 20234.

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# PENETRATION RESISTANCE OF CONCRETE—A REVIEW

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The mechanisms accounting for the failure of concrete under impact and impulsive loads, and the factors controlling the resistance of concrete to such loads, have been reviewed. It was found that little is known concerning the damage mechanism within concrete in response to dynamic loads. Apparently, the dynamic tensile strength of concrete has an important effect on its impact and impulsive resistances. A model based on the propagation of stress waves, which appears to give some insight to important material variables is described.

Types of concrete which may merit evaluation for constructing structures subjected to dynamic loads are identified and discussed.

Key words: concrete; dynamic properties; fiber-reinforcement; impact; impulsive loading; penetration resistance; reinforcing bars; stress waves.

## 1. INTRODUCTION

The design of security barriers, the materials used therein, and other protective structures have not changed significantly over the past 30 years. Many of the present practices are based on the Corps of Engineering Manual "Fundamentals of Protective Design" published in 1946 [1].[1] While this manual remains as the authoritative source in the open literature, remarkable improvements and changes in the types and properties of structural materials have been achieved since 1946. The need to improve the penetration resistance of security barriers was clearly demonstrated by Moore [2]. He showed that human-passable openings could be developed in security barriers in surprisingly short times using readily obtainable portable tools and explosives. In many instances, these openings could be produced so quickly that a reappraisal of the use of these barriers for physical security applications was required. Of the materials tested, only concrete materials gave any worthwhile resistances, but even some of them could be breached in an unacceptably short time. Penetration resistances of some concretes are given in table 1. Note that the listed penetration tools and materials would pose no difficulty in transportation or use by a small group of would-be intruders.

The National Bureau of Standards is carrying out a study for the Defense Nuclear Agency to identify structural materials that could be used in constructing barriers with improved penetration resistances. In the first part of this study, the response of concrete to dynamic loading and its resistance to impact and impulse has been reviewed and analyzed. The results are presented in this report. In addition, a preliminary analysis of the mechanisms controlling the response of concrete to impact and impulsive loading is given.

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*Center for Building Technology, National Engineering Laboratory.

[1] Numbers in brackets refer to references in appendix A.

TABLE 1. *Penetration resistance of concrete walls [3]*

| Wall construction | Materials | Penetration technique | Penetration time[a] |
|---|---|---|---|
| 8-in-thick reinforced concrete wall | 3000 psi concrete, one layer of No. 5 rebar on 6 in centers | 6 lb of explosive and hydraulic boltcutter | 3.1 ± 0.6 min |
| 12-in-thick reinforced concrete wall | 5000 psi concrete, 5/16 in expanded metal on 2.5 in centers | cutting torch, sledgehammer, and 6 lb of explosive | 2.3 ± 0.5 min |
| | | 20 lb of explosive and 36 lb temper plate | 2.0 ± 0.4 min |
| 12-in-thick reinforced concrete wall | 3000 psi concrete, one layer of No. 4 rebar on 6 in centers | 25 lb of explosive | 2.2 ± 0.5 min |
| 18-in-thick reinforced concrete wall | 3000 psi concrete, two layers of No. 4 rebars on 6 in centers | 20 lb of explosive and boltcutter | 3.9 ± 0.8 min |

[a] Time required to produce a human-size hole.

## 2. CONSTITUENTS AND TYPES OF CONCRETE

Constituents and types of common concrete are briefly described to assist readers not knowledgeable in concrete technology.

The constituents of normal weight unreinforced concrete are hydraulic cement, water, fine aggregate (e.g., sand), and coarse aggregate (e.g., crushed stone) [4,5]. Portland cement is at present the most widely used hydraulic cement for mass construction. Blended cements, which are mixtures of Portland cement and fly ash or blast furnace slag, are gradually replacing simple Portland cement in many applications. Often chemical admixtures are added during mixing of the constituents of concrete to improve certain of the characteristics of the concrete. The function of admixtures commonly used are to adjust the set, water reduction, and air entrainment.

The performance characteristics of concrete can be modified by the incorporation of polymeric systems (usually organic, although sulfur has been used). Three main types of concrete-polymer systems have been developed [6]: polymer-impregnated concrete (PIC), polymer concrete (PC), and polymer-Portland cement concrete (PPCC). PIC is a hydrated Portland cement concrete that has been impregnated with a monomer which is subsequently polmerized in situ; PC is a composite material formed by mixing aggregate with a monomer which is then polymerized; and PPCC is produced by adding either a monomer or polymer to a fresh concrete mixture, and subsequently curing the concrete and polymerizing any monomer in place.

Because concrete has a low tensile strength, it is reinforced with steel when used for structural purposes, i.e., tensile stresses are transferred to the reinforcing steel. Types of reinforcement include discrete small steel fibers (glass and polymeric fibers may also be used), steel reinforcing bars, and pre- and poststressed steel tendons.

## 3. CLASSIFICATION OF LOADS

The loads on a structure may be classified according to their duration and variation in time characteristics [7] as follows:

(1) static: loads are independent of time;
(2) dynamic: loads are dependent of time;
(3) gradually applied: rate of loading change is small compared to the natural period of the system;
(4) harmonic: loading changes in a periodic manner with time;
(5) transient: loads are applied or changed in a nonharmonic fashion.

Load classifications (3), (4), and (5) are subclassifications of the dynamic load category. Transient loads themselves may be further divided depending on their duration, pulse shape, and time of rise to maximum value. The ratio of load duration to characteristic response time of a material can also be used to subdivide transient loads (table 2). Short pulses are usually characteristic of impact or impulsive loads. Impact loads involve solid bodies while impulsive loads are essentially massless. A shock load is an intense impulsive load of extremely short pulse duration.

TABLE 2. *Load classification [8]*

| Load classification | $\tau / T$[a] | Type of load |
|---|---|---|
| Quasi-Static | $>4$ | Mechanical testing of concrete |
| Quasi-Impact | $\sim 1$ | Earthquake loading on a building |
| Impulsive and Impact | $<0.25$ | Falling weight impact, projective, explosives |
| Shock Loads | $<10^{-6}$ | High energy explosives |

[a] $\tau / T$ is the ratio of load duration ($\tau$) to characteristic response time ($T$).

## 4. MECHANISMS OF IMPACT OR IMPULSE DAMAGE TO CONCRETE

Concrete security barriers may be attacked with a variety of penetration devices ranging in energy from sledgehammers to explosives and ballistic weapons. When concrete is subjected to intense dynamic loads three major fracture regions are usually formed (fig. 1). They are a crater region, region of crushed aggregate, and a region in which the concrete has undergone extensive cracking [9]. In addition, scabbing can occur. Scabbing is the violent separation of a mass of material from the opposite face of a plate or slab subjected to an impact or impulsive loading [10].

The mechanisms through which concrete is damaged by impact or impulsive loading are considered to be somewhat similar, and therefore they are discussed together. These mechanisms are only qualitatively understood but their analysis provides a conceptual model of the processes taking place. A crater is produced at areas where concrete is subjected to impact or to contact- or near-contact explosions. The crater is produced as the result of concentrated forces at the surface of the concrete. The forces are transmitted inward, thereby crushing the concrete in the crater region. The shape and size of the crater depends on the dynamic loading process as well as the strength of the concrete. The crater volume appears to vary approximately inversely with the square root of the concrete's compressive strength. Increasing the compressive strength by 50

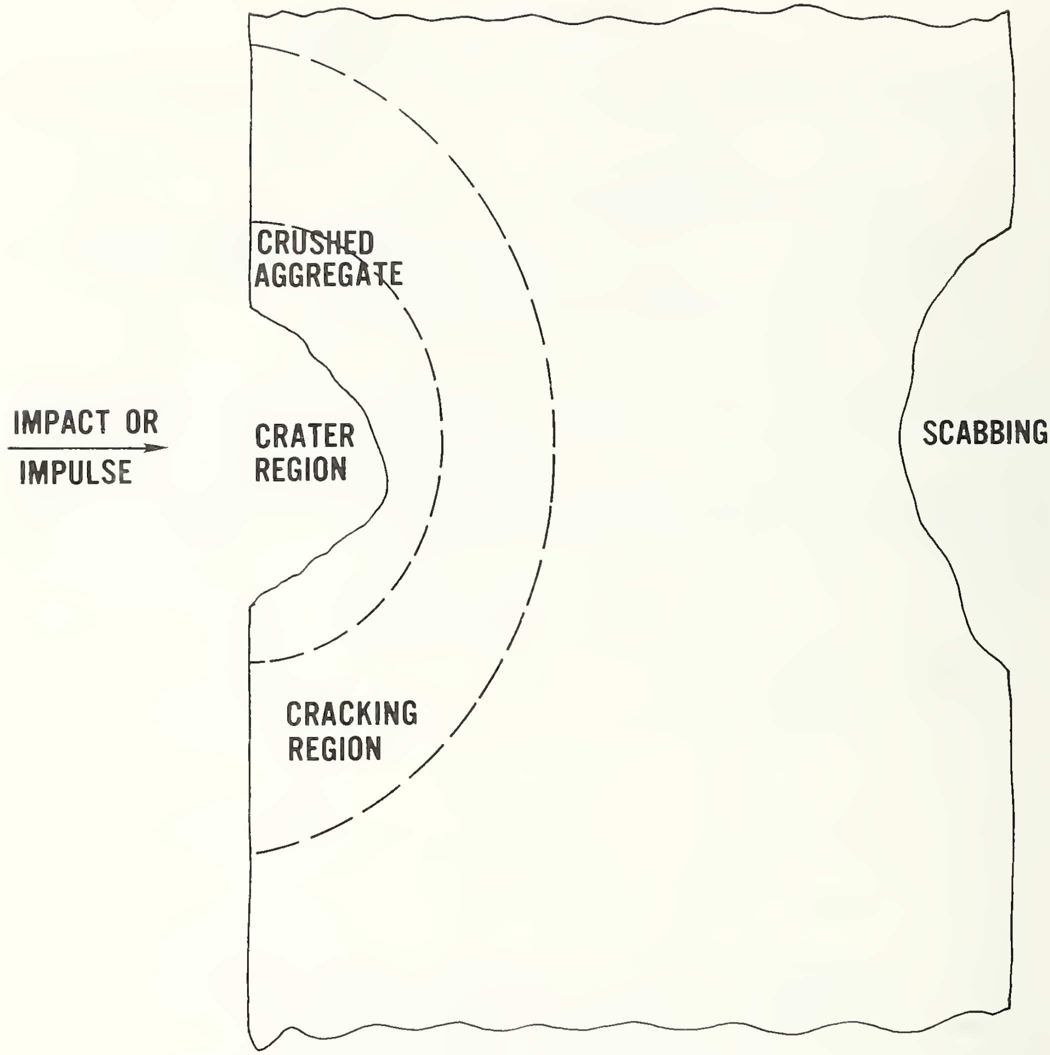


FIGURE 1. *Fracture regions in concrete subjected to an impact or impulsive load [9].*

percent may, therefore, decrease the crater volume by about 25 percent. For concrete with a compressive strength of around $4 \times 10^3$ psi, the following empirical equation relates the crater volume ($V$) caused by an explosion to the total impulse ($J$) of the explosion [8]:

$$V\ (\text{in}^3) = 1.5\ J\ (\text{lb-s}). \tag{1}$$

Other than this and similar empirical relationships, little information is available on the material behavior of concrete in the crater region.

The processes taking place in the crushed aggregate region are even less well understood. This region probably can be regarded as a transition region in which concrete has both plastic and elastic response to impact or impulsive loading. The concrete in this region is fractured by the original compressive wave and, possibly, further fractured by reflected tensile waves.

The volume of the cracking region is considerably larger than the volume of the first two regions combined [11,12], and the processes taking place in this region are considered to be better understood. The cracking mechanism is thought to involve the propagation of elastic stress waves at a finite velocity with little dispersion and attenuation from the area first experiencing the impact or impulsive loading. A compressive or longitudinal wave generated at the impact area propagates spherically into the concrete with an elastic wave velocity ($C$) approximated by [10]:

$$C = \left(\frac{E}{\rho}\right)^{\frac{1}{2}} \tag{2}$$

where $E$ is the dynamic modulus and $\rho$ is the mass density.

The compressive wave propagates to the opposite free surface of the concrete and is reflected at normal incidence as a tensile wave [12,14]. This tensile wave interferes with the wave train of the original compressive wave. The resulting wave is the algebraic sum of the waves, first decreasing compressive and then increasingly tensile (fig. 2). If the stress amplitude of the tensile wave exceeds the dynamic tensile strength of the concrete, fracture occurs. This fracturing primarily takes place in the cracking region. The tensile wave upon meeting a free surface will be reflected as a compressive wave and the process will be repeated with the possibilities of further damage occurring until the resulting stress amplitudes of the waves are dampened to below the dynamic tensile strength of the concrete. Scabbing occurs when the resultant amplitude of the incident compressive and reflected tensile waves builds up near the surface to cause tensile stresses which greatly exceed the dynamic tensile strength of the concrete [10,15].

This simplified analysis treats structural concrete as a homogeneous material free from characteristic or specific impedance[2] mismatches. Because impedance mismatches do exist in concrete, internal stress wave reflections can occur. For example the ratio of reflected stress ($\sigma_R$) to the transmitted stress ($\sigma_T$) at the interface between concrete and steel can be estimated using the following impedance mismatch equations (derivation outlined in app. B).

$$\sigma_T = \frac{2\rho_2 C_2}{\rho_2 C_2 + \rho_1 C_1} \sigma_I \tag{3}$$

$$\sigma_R = \frac{\rho_2 C_2 - \rho_1 C_1}{\rho_2 C_2 + \rho_1 C_1} \sigma_I \; . \tag{4}$$

Thus

$$\frac{\sigma_R}{\sigma_T} = \frac{\rho_2 C_2 - \rho_1 C_1}{2\rho_2 C_2} \tag{5}$$

where $\sigma_I$ is the incident stress and where $\rho_2 C_2$ and $\rho_1 C_1$ are the impedance for steel and concrete, which have the values of 250,965 lb-s/ft$^3$ and 52,750 lb-s/ft$^3$, respectively [16]. Then

$$\frac{\sigma_R}{\sigma_T} = \frac{250{,}965 - 52.750}{501.930} = 0.39 \tag{6}$$

Since $\sigma_R/\sigma_T = 0.39$, the incident wave is being partially transmitted and reflected at the concrete-steel interface. Furthermore, because $\rho_2 C_2 >> \rho_1 C_1$ the resulting sign is positive and both the reflected and transmitted waves have the same stress form as the incident wave (i.e., if the wave is compressive the reflected wave is also compressive). Also, from eq (3), the stress of the

[2] Characteristic impedance is a material property equal to the product of density and longitudinal wave velocity, i.e., $\rho C$.

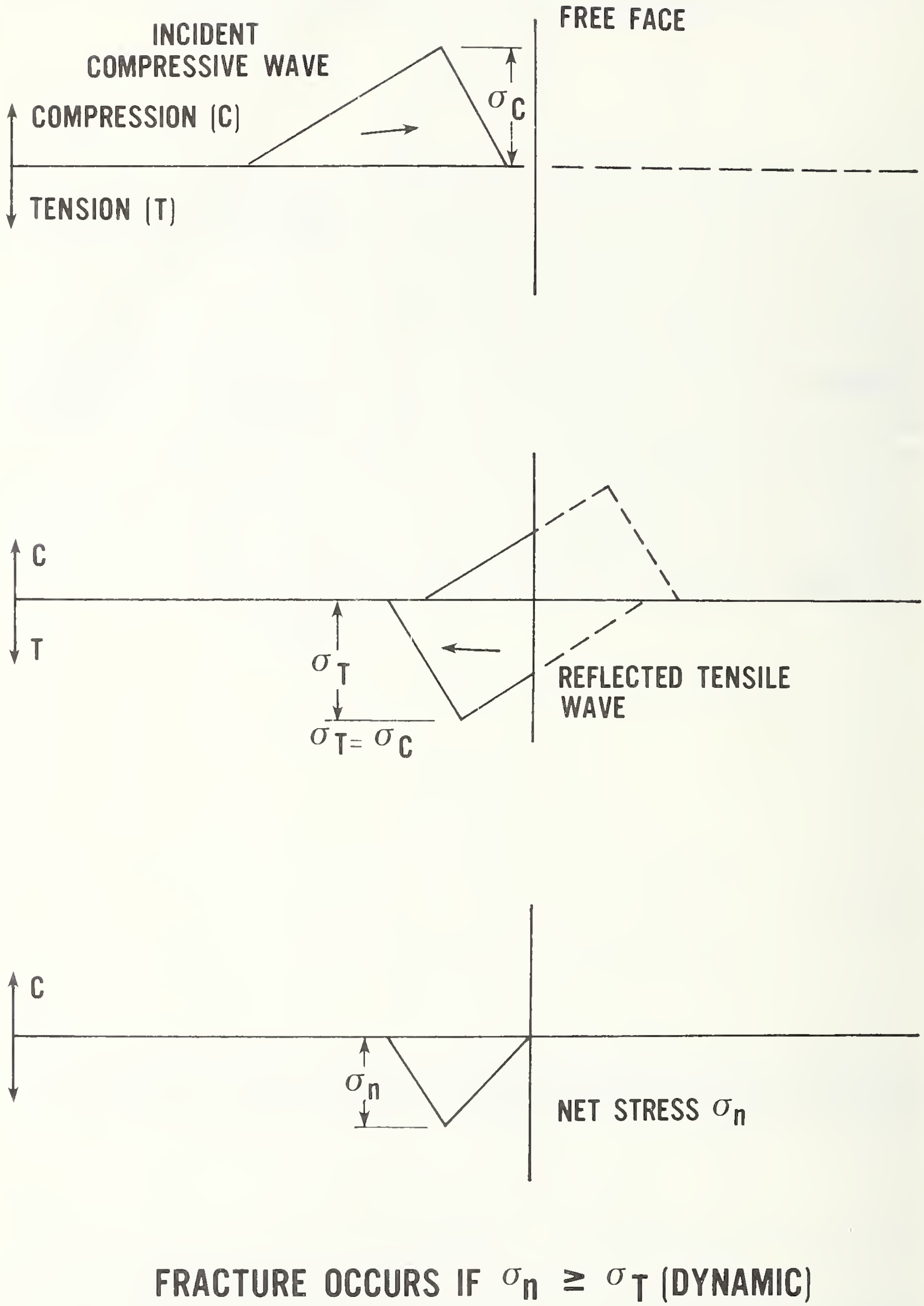


FIGURE 2. *Propagation of stress waves and fracture of concrete.*

wave being transmitted through the steel is about 1.7 times the stress of the incident wave. When this wave propagates to the interface between steel and concrete, the following results are obtained:

$$\frac{\sigma_R}{\sigma_T} = -2.9 \tag{7}$$

$$\sigma_T = 0.42\,\sigma_I \tag{8}$$

$$\sigma_R = -1.9\,\sigma_I \tag{9}$$

These results indicate that once the stress wave enters the steel, it is largely trapped there, with a change in stress form occurring at each reflection at the steel-concrete interface. Of course, these reflected waves will diminish in intensity due to inelastic losses and to interaction with other waves.

In contrast to steel, voids and cracks in concrete have very low impedances that are negligible if they are filled with air. Thus, at an interface between concrete and a large air void or crack, or at the free surface of concrete, eqs (4) and (5) predict that the wave will be almost totally reflected with a change in stress form and with the same stress intensity as the incident wave (this presumes that the air gap is sufficiently large that vibrating particles cannot transcend the space).

Impedance mismatches also occur between the cement matrix and aggregates, with the impedance of the aggregate being higher than that of the cement paste [17]. Similar to the case of steel, a portion of the original compressive wave propagates into aggregate, stressing it in compression, in addition, the reflected wave stresses the cement paste matrix in compression. Close to the impact area, the interaction between the original compressive wave train and the reflected wave can cause further damage to the cement paste matrix.

Concrete has an elastic response to the initial compressive and tensile stress waves, and these waves are only slightly dispersed and attenuated [9,18,19]. Concrete, therefore, behaves as an elastic solid, free of discontinuities. Appreciable wave attenuation appears to occur only when cracked regions are formed. This suggests that, by artificially creating some type of a microcrack system in concrete, its wave damping capability could be improved and damage by dynamic loads reduced.

## 5. DYNAMIC PROPERTIES OF CONCRETE

The majority of tests on the mechanical properties of concrete have been performed under quasi-static loading conditions, and relatively little is known about the dynamic properties of concrete. Some of the important response features of concrete to quasi-static loads include [20] :

(1) Nonlinear stress-strain (constitutive) behavior.

(2) Volume increase (dilatancy) due to action of shear stresses.

(3) At low hydrostatic compression, concrete has an elastic response (no permanent set), while at high pressures permanent deformations occur.

(4) Response of concrete is rate-dependent.

The dynamic mechanical properties of concrete are considered to be more important than the static properties in controlling the resistance of concrete to impact or impulsive loading. The dynamic mechanical properties of concrete are known to be strain rate dependent, increasing with the strain rate. For example, the tensile strength of unreinforced and reinforced concrete was reported [16] to increase by between four to five times when the loading rate was raised from 4 psi/s to around $4 \times 10^7$ psi/s. The dynamic compressive strength of concrete has been reported to be 1.3 to two times the static value [16,21], the dynamic modulus to be about 1.5 times the static value, and the impact resistance of concrete was observed to increase with the loading rate [21]. It is therefore apparent that an increase in the loading rate can significantly increase the ultimate strength of concrete [21].

Factors responsible for these loading rate dependencies are thought to be associated with the formation and growth of microcracks and with creep. These are time-dependent processes and as the loading rate increases, the time available for their manifestation is decreased. At high loading rates, the response of concrete appears to be largely controlled by pre-existing cracks.

Because concrete subjected to an impact or impulsive load largely undergoes tensile failures, its tensile strength should be one of the important considerations when selecting a concrete to be used in security barriers. The dynamic tensile strength of concrete can be directly determined using a testing machine capable of high loading rates, or indirectly evaluated in terms of the critical fractures strain energy ($U_{cr}$). $U_{cr}$ is obtained by impacting the end of a long cylindrical concrete bar with a projectile which sets up a compressive wave in the bar [22]. The compressive wave propagates to the opposite end of the bar and is reflected as a tensile wave. The intensity of the reflected tensile wave is measured using strain gages and the value of strain which causes fracture is called the critical fracture strain $\epsilon_{cr}$.

The relationship between $\epsilon_{cr}$ and $U_{cr}$ is given by:

$$\epsilon_{cr} = \left(\frac{6U_{cr}}{EAC}\right)^{\frac{1}{3}} \epsilon^{\frac{1}{3}} \qquad (10)$$

where $E$ is the modulus of elasticity, $A$ is the cross-sectional area of the concrete bar, $C$ is the wave velocity in the concrete, and $\epsilon$ is the straining rate.

Associated with $\epsilon_{cr}$ is the specific time ($RT$), the time from when the fractured area begins to be strained to when fracture occurs. The following equation gives the relationship between $\epsilon_{cr}$ and $RT$:

$$\epsilon_{cr} = \left(\frac{6U_{cr}}{EAC}\right)^{\frac{1}{2}} \cdot \left(\frac{1}{RT}\right)^{\frac{1}{2}}$$

Birkimer and Lindeman have suggested [22] that a strain energy fracture criterion could be developed for concrete subjected to dynamic loading. Sierakowski et al. [23] have proposed that cumulative tensile strain energy is better criterion (cumulative tensile strain energy is the area under the strain energy-specific time curve).

The resistance of concrete to dynamic loading has also been determined by impact strength measurements based on falling mass and ballistic pendulum test methods. Green [24] proposed that the impact strength determined by pendulum tests should be related to the ability of concrete to withstand repeated blows and to absorb energy. He found that the impact strength of Portland cement concrete increased with the static compressive strength of the concrete, while little correlation between modulus of rupture and impact strength was observed. Results from other impact tests have indicated that concretes with intermediate compressive strengths appear to have the greatest impact resistance, and that impact strength is more closely related to tensile strength than to the compressive strength of concrete [25]. Moore and McNeill [17] observed a lack of correlation between the quasi-static compressive strength and the resistance of several types of concrete to projectile impact. It appears that relationships between the impact and impulsive resistance of concrete and its dynamic properties are not well developed. However, the dynamic tensile strength of concrete does appear to be an important property in controlling the resistance of concrete to scabbing and to internal fracture by stress wave propagation.

# 6. COMPOSITIONAL EFFECTS ON THE DYNAMIC PROPERTIES OF CONCRETE

## 6.1 Portland Cement Concrete

The dependence of the quasi-static mechanical properties of Portland cement concrete on compositional variables is probably the most often studied aspect of concrete. In contrast, little is known of the relationships between composition and the dynamic properties of concrete. In this section, relationships for the quasi-static properties are examined first, and then relationships for dynamic properties. Compositional variables that have the most significant effects on the quasi-static strength of Portland cement concrete are [25,26]:

(a) water-to-cement ratio,

(b) cement-to-aggregate ratio,

(c) grading, surface texture, shape, strength, and modulus of elasticity of aggregate particles, and

(d) maximum size of the aggregate.

With a given cement, the water-to-cement ratio is regarded as the most important variable in controlling both the strength and durability of concrete [25]. For example, for a given concrete, the compressive strength was $5 \times 10^3$ psi at a water-to-cement ratio of 0.5 and only $1.5 \times 10^3$ psi when the ratio was increased to 1.0. The water-to-cement ratio has such a severe effect because it largely determines the porosity of the hardened cement paste. Likewise, deliberately introducing porosity by using air entraining admixtures decreases the strength of concrete. An approximate relationship between compressive strength and void volume has the general form [20,27]:

$$f_c = \beta \quad \frac{V_c}{V_w + V_A}$$

where $f_c$ is the compressive strength, $\beta$ is an empirical constant depending on material, curing age, and testing conditions, $V_c$ is the volume fraction of cement paste, $V_w$ is the volume fraction of water, and $V_A$ is the volume fraction of air.

The static modulus and, probably, the dynamic modulus of elasticity of concrete can increase or decrease with the volume fraction of the aggregate depending upon whether the aggregate has a higher or lower modulus than the cement paste [28,29]. However, in the range of normal concrete proportions and aggregate quality, changes in composition variables (b), (c), and (d) do not usually change the strength by more than 10 percent.

Few studies on relationships between the impact strength of concrete and compositional variables have been reported. Green [24] studied the effects of repeated impacts using a ballistic pendulum. He found that concretes containing coarse aggregates that are angular in shape with rough surface give higher resistances to accumulated impact damage than concretes with smooth rounded aggregates. Other observations were that: concretes that absorbed less energy per impact could withstand a greater number of blows and that impact strength increased with the compressive strength of concrete. Hughes and Gregory [30] obtained similar results using the ballistic pendulum developed by Green. They showed that the main compositional variables affecting the compressive strength of concrete, i.e., variables (a) to (d), had a similar affect on the resistance of concrete to accumulated impact damage. Goldsmith et al. [19] impacted concrete bars with high velocity steel spheres and observed that the incorporation of lightweight aggregate did not increase the impact energy absorptive capacity of concrete as anticipated, even though the strain energy transmitted to concrete is largely controlled by the aggregate. It appears that further work is required to unequivocally determine the relationship between energy absorption and impact resistance of concrete.

Entraining air in concrete has been found to increase the spallation resistance of concrete subjected to impulsive loading by explosives [31]. Possibly, air voids increased the capability of concrete to dampen compressive and tensile stress waves.

## 6.2 Polymer-Modified Concretes

Modifying concrete with the incorporation of polymeric systems can dramatically improve the static mechanical properties and durabilities of concrete [32]. For example, typical improvements in strength for polymer impregnated concretes with poly(methyl methacrylate) are approximately fourfold increases in compressive, shear, and tensile strengths, threefold increases in the modulus of rupture, and twofold increases in the modulus of elasticity [33]. Large improvements in strength properties have also been observed for epoxy-impregnated [34] and sulfur-impregnated concretes [35]. Although many studies have been performed on the static mechanical properties of polymer-modified concretes, little attention has been given to their response to dynamic loading.

Steinberg et al. reported [33] that concrete impregnated with methyl methacrylate (MMA) had improved resistance to 30-06 armor piercing ammunition when compared to untreated concrete. For example, holes and craters produced by the armor-piercing projectiles were also smaller for the impregnated concrete. Moore and McNeill [17] studied the response of a series of polymer-modified concretes to 30-06 armor piercing ammunition. Concretes with the most improved impact properties were styrene-polyester polymer concretes, polymer-impregnated concretes with MMA and butyl acrylate, and latex-modified concretes. The latex-modified concrete was found to be by far the most promising material. By the inclusion of 7 to 10 percent of a latex emulsion (based on weight of Portland cement) the amount of cratering was reduced almost to nil. This was significantly less cratering than observed for the polymer concretes and polymer impregnated concretes, even though the latex-modified concrete had much lower compressive strengths than the polymer concretes and polymer impregnated concretes. Crater reduction in the latex-modified concrete was attributed to the formation of a continuous film of tough flexible polymer throughout the concrete. This film apparently behaves as an attenuator for shock waves and also bonds the aggregate and cement particles together, and is thought to increase its dynamic tensile strength.

In contrast to latex-modified concrete and normal concrete, the dynamic mechanical properties of polymer-impregnated concretes do not appear to be significantly higher than their static values [36]. This behavior is probably the result of filling the pores and air voids in the cement matrix with a polymer and the formation of polymer bridges at the cement-aggregate interfaces. Thus the opportunities for the development of microcracks under dynamic loading are thereby decreased and the strength properties under both static and dynamic loadings are primarily controlled by the pre-existing micro- and macrostructural features.

## 6.3 Reinforced Concrete

Structural concrete is usually reinforced by the incorporation of steel reinforcing bars (rebars). Other forms of reinforcement include prestressed and poststressed tendons, discrete fibers, and wire fabric. In the past security barriers have been almost exclusively reinforced with rebars.

### 6.3.1 Rebar and Prestressed Reinforced Concrete

Steel rebars have been found to be relatively ineffective in reducing the depth of penetration of projectiles and bombs into concrete [1]. However, they have been found to prevent the mass separation of concrete subjected to impact or explosives, whereas, with unreinforced concrete large fragments are separated. Studies on reinforced concrete beams have qualitatively shown that both longitudinal and shear reinforcement are required for the concrete to develop resistance to impact [1]. Burgess and Allen [37] observed that reinforced concrete slabs can undergo both flexural and shear failures, with the highest impact resistance being obtained when both failure modes occurred simultaneously. The impact resistance of prestressed concrete has been compared to that of rebar-reinforced concrete by Bates [38]. He found that prestressed concrete beams have a much lower impact strength measured by single-blow impact testing than rebar-reinforced beams. However, prestressed concrete suffers less permanent deformation than rebar-reinforced concrete when subjected to a number of impacts below its impact strength. Nevertheless, under repeated impacts, the ultimate impact resistance of prestressed concrete and rebar-reinforced concrete beams designed for the same static working loads may be similar.

The mechanical properties of both prestressed concrete and rebar-reinforced concrete are strain dependent. For example, at high loading rates the required strain energy to produce a given deflection may, in beams and slabs, be as much as 40 percent above that required under static loading conditions [39]. The ratios of static strain energy to impact energy required to achieve a given deflection have been found to vary between 0.3 to 0.6, depending on the geometry of the test specimens [38,40]. Modes of failure of reinforced beams and slabs can change as loading rates are increased. In a number of impact tests, shear failures have occurred, while similar specimens failed in flexure under quasi-static loading. The probability of shear failure appears to increase with loading rate and impact energy. This is consistent with the observation that under rapid impact loading concrete responds as an elastic material. It also suggests that the resulting stress waves remain concentrated in the region of impact rather than being dissipated throughout the concrete mass.

Over-reinforcement does not appear to be effective in increasing the impact resistance of concrete. For prestressed concrete beams, there is a certain proportion of steel which gives the greatest resistance to impact [37,38]. Bates [38] recommended that sufficient steel should be in a section so that failure is due to fracture of stressing tendons while still permitting the maximum possible damage to the concrete in compression. Over-reinforcement with rebars also should be avoided, because a severe impedance mismatch exists between steel and concrete [17].

The most important factors which appear to control the impact resistance of reinforced concrete are, therefore, proportions of reinforcement, arrangement of reinforcement, and rate and intensity of loading. In addition, strength of concrete [37], type of impact (single blow or repeated blows) [38], and impact angle [37] have been found to influence the impact resistance of reinforced concrete. The tensile strength of the reinforcement as well as the bond developed between the reinforcement and concrete also probably have some effect on the impact failure resistance of concrete.

### 6.3.2 Fiber-Reinforced Concrete

A promising approach to increasing the impact resistance of concrete is the incorporation of discrete steel fibers. Steel fibers are presently commercially available in lengths of 0.25 to 2.50 in (6.3 to 63 mm) with aspect ratios[3] of 30 to 150, and in rod, rectangular, and deformed shapes. Usually between 1 percent and 5 percent fibers, on a volume basis, are randomly distributed in concrete [41]. Other types of fibers have been studied, including glass, polypropylene, and nylon.

In some cases, these fibers appeared to be more effective than steel fibers in increasing the impact resistance of concrete [42,43]. However, based on considerations of overall improvement in mechanical properties, their durability in concrete, availability and cost, steel fibers are at present the most widely used fiber reinforcement for concrete.

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[3] Aspect ratio is the fiber length divided by the equivalent diameter (diameter of a circle with an area equal to the cross-sectional area of the fiber).

Ferrocement[4] is similar to fiber-reinforced concrete except that wire mesh is used as the reinforcement rather than discrete fibers. Because ferrocement appears to have the same response to impact as fiber-reinforced concrete [13], no distinction is made between them in this report.

Among the most pertinent work on the impact resistance of fiber-reinforced concrete was that performed by Williamson [44–46]. He subjected fiber-reinforced concrete slabs containing steel rebars to explosives and compared the results obtained with plain rebar-reinforced concrete. The fibers considerably increased the shatter resistance of the concrete with an 80 percent reduction in fragmentation and 20 percent decrease in velocities of the fragments. Recently, Naus and Williamson [47] qualitatively demonstrated that fiber-reinforced concrete was more resistant to penetration and to repeated impacts by small arms projectiles than unreinforced concrete.

Fiber-reinforced concrete has also been demonstrated to be more resistant to falling mass impact than unreinforced concrete. Ramakrishnan et al. [48] subjected fiber-reinforced shotcrete[5] to repeated impacts from a 10 lb (4.5 kg) hammer falling 18 in (0.46 m). This impact force is probably less than that from the average impact of a sledgehammer. Four types of steel fibers of different shapes and tensile strengths were used. One fiber with hooked ends gave particularly good results, with increases of over 500 percent in impact resistance compared to unreinforced shotcrete. An increase in impact resistance of around 200 percent was obtained using the hooked-end fibers compared to straight fibers. This improvement was attributed to the increased bond between the hooked-end fibers and matrix. In addition, the ability of fiber-reinforced concrete to absorb impact forces was found to increase as the fiber concentration increased. Structures can be readily produced or repaired using fiber-reinforced shotcrete, so this appears to be a feasible method for upgrading old security barriers as well as for constructing multi-layer security walls.

Improvements in the impact strength of concrete when reinforced with fibers have been thought to be largely attributable to the substantial energy required to cause fiber slip and progressive debonding of fibers or fiber fracture as cracks develop [48,50]. As the fibers slip and are being pulled out of a concrete matrix, they appear to be absorbing energy, even though the matrix has cracked. However, under shock loading conditions these energy-absorbing processes may not be able to cause a redistribution of stresses. Williamson found that at a loading rate of $4 \times 10^7$ psi/s, the dynamic tensile strength of fiber-reinforced concrete was similar to that of unreinforced concrete [16]. Further, the presence of fibers did not cause any apparent attentuation or dispersion of shock-induced stress waves. Possibly, the main beneficial effect of fibers at high rates and intense loadings is to bridge cracks, thereby reducing fragmentation and absorbing increased energy.

According to the stress wave theory, the impedance mismatch between cement and steel fibers may be detrimental to the dynamic properties of fiber-reinforced concrete. It appears that the effect of the impedance mismatch is either more than compensated by the large absorbing capability of fiber-reinforced concrete, or it is small. It is likely that if the wavelength of the stress wave and the strain cross section area are much larger than the dimensions of the fiber, no interaction occurs, i.e., no change in wave form or intensity occurs at the interface between the concrete and steel fiber. For example, the wavelength of a shock wave generated in concrete by a blasting cap has been found to be around 17 in [16], compared to typical fiber diameters of 0.01 to 0.02 in and lengths of 0.25 to 2.50 in.

## 7. SUMMARY AND CONCLUSIONS

The response of concrete to dynamic loading and the accompanying failure processes are, at best, only qualitatively understood. Accordingly, improvements in the resistance of concrete to impact and impulsive loading have been largely based on empirical considerations and experiments. This approach has provided little information on material variables that may control

[4] Ferrocement is a thin-shell concrete reinforced with wire mesh.

[5] Shotcrete is mortar or concrete conveyed through a hose and projected at high velocity onto a surface.

the resistance of concrete to impact forces or impulsive energies. Application of stress wave concepts to concrete appears to give a useful conceptual model and some insight to important material variables. At present, however, relationships have not been developed to predict the magnitudes of the effects of material variables on the impact and impulsive resistance of concrete.

The dynamic tensile strength appears to be the most important mechanical property controlling the impact and impulsive resistance of concrete. Incorporation of polymers, especially lattices, in concrete seems to significantly increase the dynamic tensile strength of concrete. Other factors that may somewhat affect the dynamic tensile strength of mature concrete include the shapes and elastic moduli of aggregates, mix proportions of the concrete, and entrainment of air. Entrained air possibly could increase the capability of concrete to dampen stress waves, which suggests that microstructural modifications in concrete can improve its dynamic properties.

Obviously, structural concrete for security barriers must be reinforced with steel rebars or stressed tendons. The incorporation of steel fibers has been demonstrated to remarkably increase the impact and impulsive resistance of concrete. Fibers appear to lessen the extension of cracks and to reduce fragmentation of concrete by increasing the ability of concrete to absorb energy and by bridging cracked regions.

Thus, the types of reinforced concrete that appear to merit evaluation as materials for constructing security barriers include latex-modified concrete, fiber-reinforced concrete, a combination of latex-modified and fiber-reinforced concrete, air-entrained concrete, and polymer concrete. In addition, relationships between the impact and impulsive resistance, and between the mechanical properties, compositions and microstructures of normal concretes need to be developed.

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## APPENDIX B—STRESS DISTRIBUTION RELATIONSHIPS

Derivation of stress distribution-interfacial relationships in composite materials is started by considering an elastic wave propagating in a composite which encounters an interface between two materials, normal to the direction of propagation. The following conditions of continuity of stress and particle velocity must be satisfied at the interface [3].

$$\sigma_I + \sigma_R = \sigma_T \tag{B1}$$

and

$$V_I + V_R = V_T \tag{B2}$$

where $\sigma$ and $V$ denote stress and particle velocity, and the subscripts $I$, $R$, and $T$ refer to the incident, reflected, and transmitted wave, respectively.

The relationship between the intensity of stress and particle velocity in a material is:

$$\sigma = \rho C V \tag{B3}$$

thus

$$V = \frac{\sigma}{\rho C} \tag{B4}$$

where $\rho$ is density and $C$ is wave velocity.

Let the material in which the incident wave is propagating be denoted by the subscript 1 and the subscript 2 denote the second material. Then:

$$V_I = \frac{\sigma_I}{\rho_1 C_1} \tag{B5}$$

and

$$V_R = \frac{-\sigma_R}{\rho_1 C_1} \tag{B6}$$

The negative sign in eq (B6) arises because the reflected wave is traveling in an opposite direction to the incident wave.

The transmitted wave is propagating in the second material, therefore:

$$V_T = \frac{\sigma_T}{\rho_2 C_2} \tag{B7}$$

Substituting eqs (B5), (B6), and (B7) into (B2), yields:

$$\frac{\sigma_I}{\rho_1 C_1} - \frac{\sigma_R}{\rho_1 C_1} = \frac{\sigma_T}{\rho_2 C_2} \tag{B8}$$

Solving eqs (B1) and (B2) for $\sigma_T$, and $\sigma_R$ in terms of $\sigma_I$ yields the following "impedance mismatch" equations:

$$\sigma_T = \frac{2\rho_2 C_2}{\rho_2 C_2 + \rho_1 C_1} \sigma_I \tag{B9}$$

and

$$\sigma_R = \frac{\rho_2 C_2 - \rho_1 C_1}{\rho_2 C_2 + \rho_1 C_1} \sigma_I \tag{B10}$$

Eqs (B9) and (B10) can be used to predict the distribution of stress at the interface between two materials.

The product $\rho C$ is a material property [48] called the impedance or specific acoustic resistance. The impedance of a material is given by the relationship [49,8]:

$$\rho C = \left( \frac{\rho E(1-\nu)}{(1+\nu)(1-2\nu)} \right)^{\frac{1}{2}} \tag{B11}$$

where $E$ is the dynamic modulus and $\nu$ is Poisson's ratio. For concrete, $\nu$ is around 0.2 so neglecting it and setting:

$$\rho C = (\rho E)^{\frac{1}{2}} \tag{B12}$$

only results in a small error. Thus the longitudinal wave velocity in concrete is approximated by

$$C = \left( \frac{E}{\rho} \right)^{\frac{1}{2}} \tag{B13}$$

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