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Behaviour of normal and steel fiber-reinforced concrete under impact of small projectiles

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Abstract

Steel fiber-reinforced concrete is currently used to provide massive armours against the impact of projectiles in sentry boxes, arms and powder depots, and other defence buildings. In this paper a set of trials intended to study the main factors affecting the impact of small projectiles on steel fiber concrete targets is described. The work is also oriented to obtain a design method for steel fiber concrete barriers against small projectiles and debris. This design method is different from the two main approximations to the problem followed thus far.

Keywords: Concrete; Fiber reinforcement; Modeling; Mechanical properties

1. Introduction

Impact on normal concrete targets is not a new problem for impact engineering or concrete technology. As early as 1910, Petry [1] published his penetration formula for plain and reinforced concrete targets. Much later, in 1950, Amerikian [2] proposed some changes to Petry's formula. Other empirical contributions to the impact of small projectiles on concrete are: the formulae proposed in 1946 by the US Army Corps of Engineers (ACE) [3]; the National Defence Research Committee (NDRC) formula (1946) [4], modified by Kennedy in 1976 [5]; Berriaud et al., or CEA-EDF (French Atomic Energy Commission) (1982) [6,7]; Kar (1978) [8]; Degen (1980) [9]; Hughes (1983) [10]; and Forrestal et al. (1993) [11]. All of these formulae were designed empirically by fitting a set of data to some type of curve. The form of the curve takes into account the influence of the variables to be studied. Therefore, while some theoretical concept around the phenomenon must be known, its empirical basis restricts its application field to just that of the set of trials used in the fitting. So, these formulae do not give us any conclusions that can be checked experimentally later, and they have not been designed for special concretes like steel fiber-reinforced concrete (SFRC).

On the other hand, the use of numerical methods is mainly based on theoretical concepts. However, their use is much less common than that of empirical formulae, because a manual fitting of the model is necessary in many stages (e.g., parameters for the constitutive equations of materials, parameters for erosion, mesh and calculation algorithms, finite element design, etc.) for which a particular training is needed. Its use is also more expensive because of the amount of memory, process, and time process that must be provided. In addition, the use of numerical methods tends to overshadow the influence of macroscopic variables, which is only detected by repeated computing for various sets of the parameters pointed out above, and relating these data with experimental results. Some technical properties of concrete (which can only macroscopically be considered as isotropous and homogeneous) affecting the phenomena are very difficult to introduce into the model, such as maximum size and type of aggregate (crushed or natural, silicious or lime), compression strength, addition of fibers, and other properties related to the projectile.

We are concerned here with obtaining a model for general use that has a theoretical basis and is simple. The efforts are centered on small projectiles, so the global responses of plates or structures are not considered.

2. Materials and methods

2.1. Materials, proportioning, and batching of SFRC

Fibers added to concrete were made with cold, drawn low-carbon steel and were of the hooked-end type, collated into bundles of 25 fibres. The fiber length was 50 mm and

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the diameter was 0.5 mm; therefore, the aspect ratio was 100. Portland cement was used with a minimum strength of 45 MPa at 28 days (I-45A type in accordance with Spanish cement standard). The fine aggregate was natural sand with a fineness modulus of 2.78. The coarse aggregate was crushed silicious stone. The degradation coefficient in the Los Angeles machine was equal to 27.2%. Mix proportioning per cubic meter is shown in Table 1.

Concrete without fibers was designed to reach a characteristic strength of 40 MPa at 28 days, and was measured on cylindrical specimens with diameter of 150 mm and length of 300 mm.

Fibers were added to concrete at 40, 80, and 120 kg of fibers per cubic meter of concrete; this is equivalent to 0.5, 1.0, and 1.5 percent by volume of concrete.

2.2. Plates and projectiles

With the concrete described above, a large set of SFRC plates was made with different thicknesses and fiber dosages. The thickness varied from 4 to 20 cm; the quantity of fibers is indicated in Table 2. Dimensions of the front face of the plates were 60 × 60 cm. Dimensions of the front face must be greater than a certain value so that edges do not influence the impact or penetration of bullets. The number of hits that can be withstood by one plate also depends on the dimensions of its front face. With a front surface of 60 × 60 cm, it is possible to fire at least five hits with 5.56-mm projectiles, three hits with 7.62-mm Armour Piercing (AP) projectiles, or one hit with a 12.7-mm AP projectile, although the addition of fibers increases this amount very much. Problems in transporting the plates to the experimentation site also limit their larger dimensions. In Table 2 all plates are classified by thickness and quantity of fibers.

Four plates of 10-cm thickness, two without fibers and other two with 80-kg/m^3 of fibers, were hit with some "tricked" 5.56-mm bullets: the powder contents of their cartridges were reduced by 10 and 20% to asses the effect of a smaller impact velocity on penetration. The same was done with four plates of 12-cm thickness and with the 7.62-mm AP bullet.

The projectiles used were: 5.56 × 45 mm (SS 109 NATO), 7.62 × 51 mm AP, and 12.7 × 99 mm AP. The mass of bullets and their hard cores are shown in Table 3. All projectiles were fired 30 m from the target. The composition, structure, and weight of each projectile are very important for its performance, as will be seen later. It is necessary to know the total mass of the projectiles, as well as the hard core mass for AP projectiles. As can be seen in Table 3, a 5.56-mm projectile has a much smaller hard core than the other ones in proportion to full mass of the projectile. Also, the 5.56-mm projectile is structurally very different from the others: its hard core is just in the nose of the projectile; the 7.62- and 12.7-mm AP projectiles have their hard cores in the rear of the projectile. These two projectiles have approximately the same hard core proportion to total mass (47.4 and 54.3%, that is, around 50%).

2.3. Test set up, measures, and measuring devices

For each hit both the impact and residual velocity (if any) were obtained by radar, making use of the Doppler effect (see Figs. 1 and 2). Obtaining the residual velocity requires the bullet signal to be distinguished from those coming from fragments produced on impact. This is relatively easy since the mass of the hard core of the projectile, which leaves from the rear side of the plate, and/or its residual velocity were greater than those of the fragments. From this point of view, the signal from the 5.56-mm projectile was the most difficult to catch after its impact.

The penetration depth (if the projectile stopped inside the plate) was measured by flexible and rigid bores. Measurement by flexible sounding bore is the actual maximum length of flexible bore that can be introduced into the path of projectile up to its rear face. Deviation with regard to initial penetration path is not likely to occur for those hits causing total perforation of the plate. However, this effect is very important for penetration depth in those hits not causing perforation, in which cases deviation is always present.

Besides this, the maximum depth and minimum and maximum diameter were measured on each spall crater. However, these data do not allow us to obtain any quantitative conclusions, but rather qualitative estimations.

Table 1
SFRC mix proportions

Cement I-45A	Sand	Fine gravel	Water	Superplasticizer
400 kg	980 kg	851 kg	1771	5.5 kg

Table 2
Number of plates tested

	Quantity of fibers (kg/m^3)			
Thickness (cm)	0	40	80	120
4	4	0	4	1
6	10	2	10	2
8	8	0	8	2
10	10	0	10	2
12	8	0	8	0
14	0	2	2	2
18	0	2	0	2
20	0	0	0	2

Table 3
Mass of bullets and their hard cores

Caliber	Full mass (g)	Hard core mass (g)	% core on full mass
5.56 × 45 mm	4.130	0.495	12.0
7.62 × 51 mm AP	9.700	4.600	47.4
12.7 × 99 mm AP	42.000	22.800	54.3

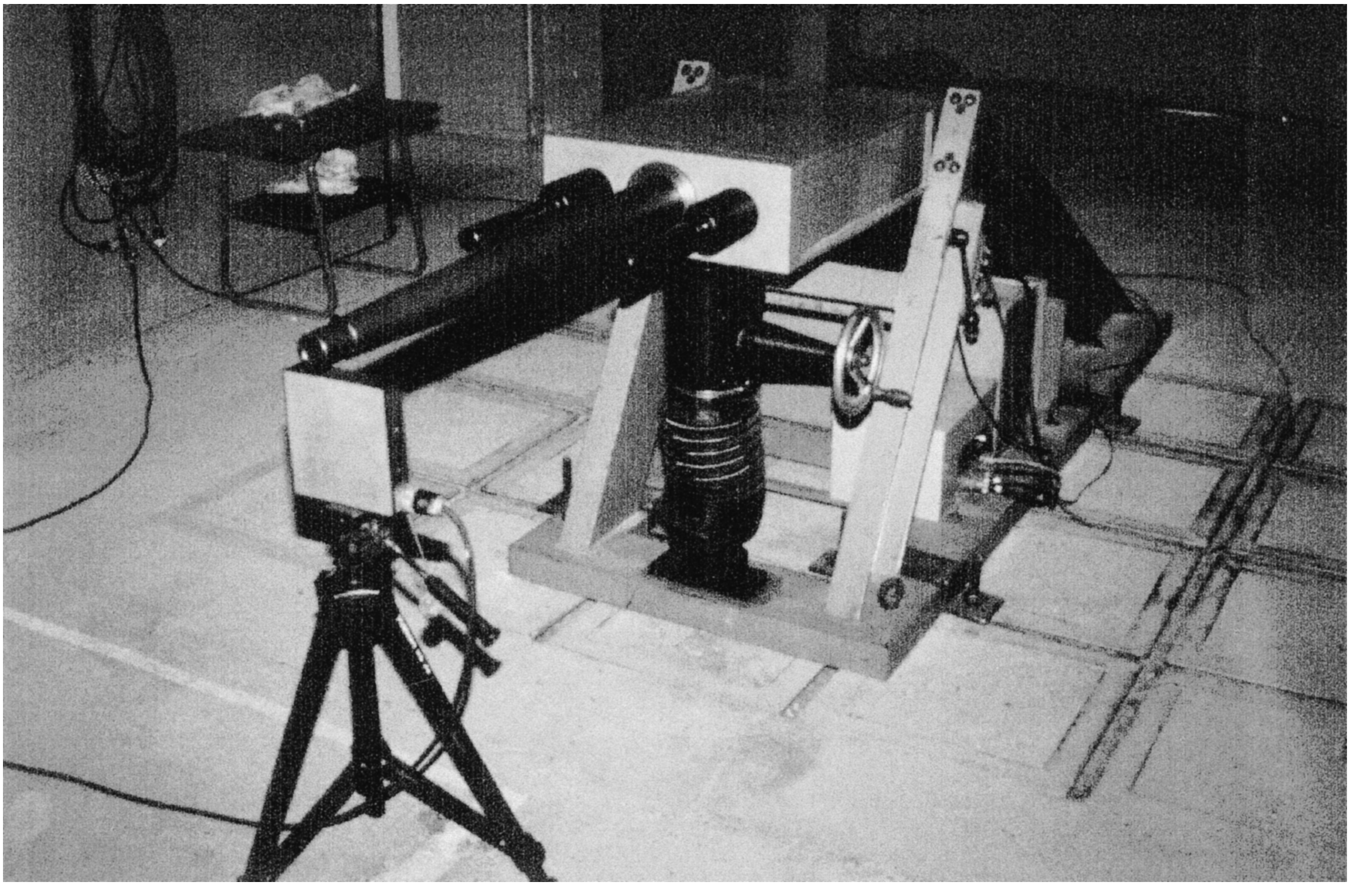

Fig. 1. Test gun with transmitter-receiver antenna of Doppler equipment.

2.4. Study of perforation

Although we will later comment on its validity, we are going to calculate the kinetic energy of a projectile as $E = 1/2\ mv^2$, where m is the initial or full mass of bullet and v is either impact or residual velocity of bullet if we calculate initial or residual kinetic energy, respectively. In some trials the initial velocity of the projectile was reduced by removing from the cartridge a predetermined percentage of powder (10 or 20%, as noted above).

With data acquired in the field, we can calculate the kinetic energy loss to thickness of plates ratio ($\Delta E/t$) for all hits having perforated the target. The data points are grouped by projectile type and fiber dosage, regardless of thickness of plate or initial velocity of the bullet, obtaining the mean and standard deviation of each group. Results are shown in Table 4. They are expressed in Joules per centimetre (J/cm) so as to obtain comparable numbers.

It is important to point out that the standard deviation is about 5 to 8% of the average value. These coefficients of variation are very good for building materials tests and it shows us that $\Delta E/t$ can be adopted as a material characteristic; at least, it is independent of thickness or impact velocity for certain conditions that will be mentioned below. If we assume a normal distribution for $\Delta E/t$, its actual value would be around the average $\pm$5–8% with a probability of 68.27%, or around the average value $\pm$10–16% with a probability of 95.45%, regardless of the thickness of the target or initial velocity of the bullet. Therefore, this factor, $\Delta E/t$, characterizes each concrete with a certain fiber volume as to its resistance to the impact of each type of projectile, regardless of its velocity range or the thickness of the barrier. $\Delta E/t$ can be considered as an aleatoric variable or, by means of some theory, to reach the conclusion that it is theoretically a constant value K, which can be estimated by average value for $\Delta E/t$. In any case, we can define a characteristic value for $\Delta E/t$; that is, a value with a probability of 95% to be overcome. With this characteristic value, which will be called K_{cr}, we can calculate the perforation threshold thickness, as limiting case of definition of K_{cr} or $\Delta E/t$. As $K_{cr} \leqslant E_i - E_s/t$, if we assume E_s (residual kinetic energy) $= 0$, we will ideally obtain an upper limit for the perforation threshold thickness as [see Eq. (1)]:

$$t_{perf} \leqslant \frac{E_i}{K_{cr}} \tag{1}$$

with E_i the initial kinetic energy. If this is correct, the following inequality must also be fulfilled [see Eq. (2)]:

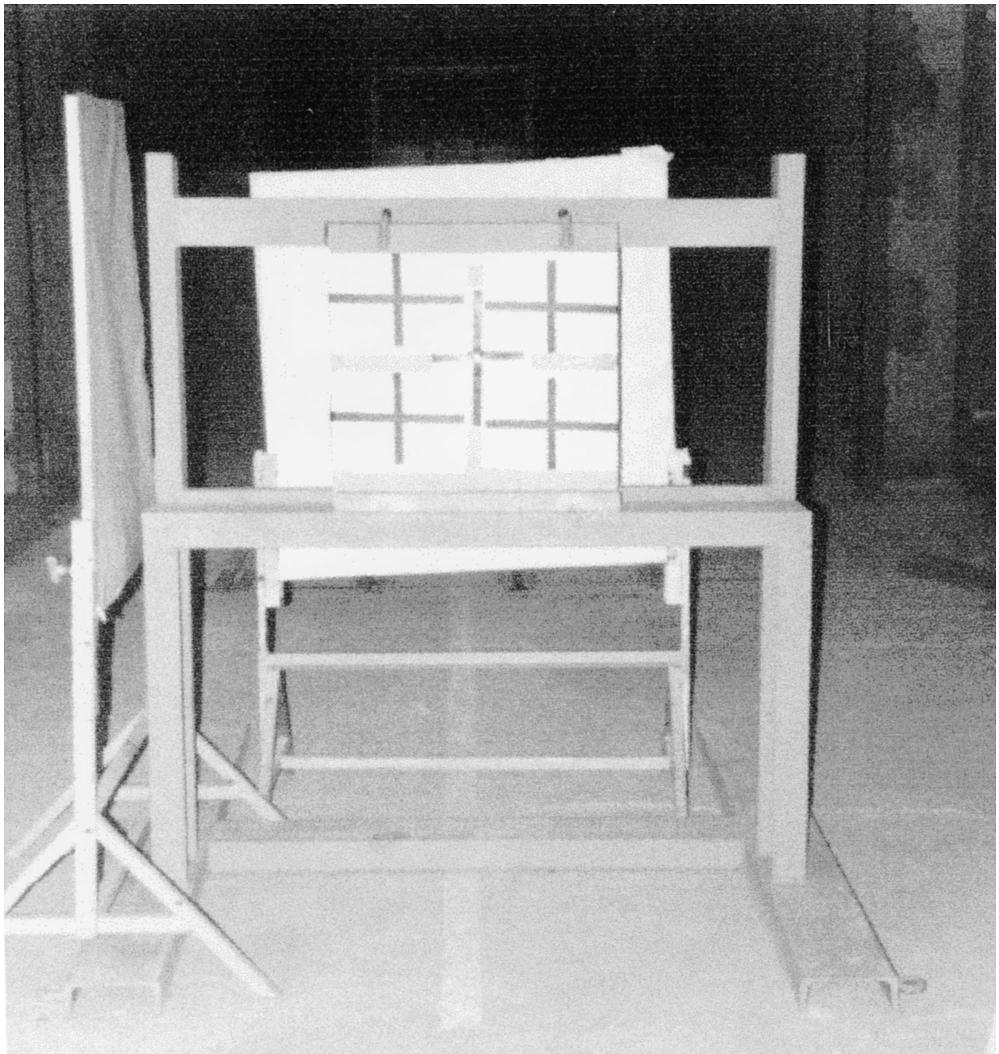

Fig. 2. Metallic frame supporting a steel fiber-reinforced plate.

$$\left[\frac{E_i}{t}\right]_{perf\,1} \leqslant \frac{\Delta E}{t} \leqslant \left[\frac{E_i}{t}\right]_{perf\,2} \qquad (2)$$

where:

$\left[\frac{E_i}{t}\right]_{perf\,1}$ = higher value for E_i/t between those hits *not* having perforated the target

$\left[\frac{E_i}{t}\right]_{perf\,2}$ = lower value for E_i/t between those hits having perforated the target

With data obtained in the field, any possible value for $\Delta E/t$ (Table 4) must be in the range defined by inequality [Eq. (2)] for all combination of projectiles and fiber ratios used in this work. The lower and higher values obtained for each combination appear in Table 5. In that way, we have a valid and accurate enough expression to obtain the perforation threshold thickness.

We have to point out that value K as defined above is independent of the values reflected in Table 5: the first is obtained from those hits having perforated the target and taking into account residual velocity of the projectile, whereas the values in Table 5 are independent of the residual veloc-

Table 4
Values of $\Delta E/t$ for hits perforating the target

Caliber (mm)	Fiber ratio (kg/m^3)	Average (J/cm)	Standard deviation (J/cm)	Number of data points
5.56	0	320	21.00	8
5.56	80	345	20.45	8
7.62 AP	0	394	25.02	4
7.62 AP	80	403	27.00	22
12.7 AP	0	1022	84.06	11
12.7 AP	40	1035	43.81	6
12.7 AP	80	1048	86.20	37
12.7 AP	120	1130	85.00	20

Table 5
Experimental results from Eq. (2)

Caliber	Fiber ratio	Minimum value	Maximum value
5.56	0	253	380
5.56	80	255	374
7.62	0	360	474
7.62	80	360	479
12.7	0	800	1294
12.7	40	875	1139
12.7	80	890	1124
12.7	120	879	1149

ity and are obtained from hits having and *not* having perforated the target.

Considering the loss of kinetic energy on penetration as $1/2\ m\ (v_i^2 - v_f^2)$ is only possible by assuming the mass of projectile to remain constant just inside the plate; this term is the main kinetic energy source of the projectile. The loss of mass for AP projectiles is less than the loss for more deformable projectiles because of its hard core. In any case, it can always be assumed that loss of mass is concentrated just on the impact, and the penetration occurs for constant mass equal to the mass of the hard core of the projectile only. But it is easier to find from catalogues of projectiles the global mass of projectile only; therefore we have calculated $\Delta E/t$ with this global mass. This point introduces an unknown scale factor within these parameters also, but it does not affect practical calculations with them, since this scale factor affects in the same way both calculation of kinetic energy and calculation of factor K.

This K value can be independent of thickness or impact velocity under only certain conditions. When the velocity of the projectile is less than the velocity of the shock waves inside the concrete, the projectile will be braked by a strongly damaged material whose residual strength against projectile advance can be assumed to be independent of external factors, such as velocity of projectile or thickness of the barrier. This would be incorrect if the velocity of the projectile is greater than or of the same order as the velocity of the shock waves. Also, it will not be true if the projectile is very slow, thus creating a global response of the barrier (e.g., a response as a plate).

On the other hand, $\Delta E/t$ or K is dependent on the type of concrete (compressive strength, quantity of fibers, and any outstanding property) and type of projectile. But a scale factor exists between values $\Delta E/t$ corresponding to similar projectiles. Here, the concept of similarity is related to the geometry and internal structure of the projectile (geometric scale) and to the ratio between hard-core mass and total mass, if both are made with the same materials.

In our case, the 5.56 projectile is very different from the 7.62 or 12.7 AP: its hard core is smaller compared with its total mass. In addition, its small core is placed just on its nose; the 7.62 and 12.7 AP projectiles have a hard core equivalent to 50% of their total mass, and these hard cores are placed on their rear face and a geometric scale factor exists between their dimensions. In Table 6 are shown some values of K/ϕ^2 (these are the average values for $\Delta E/t$ from Table 4 divided by the square caliber ϕ^2 for each projectile). It is worth noting that these values are always very close for 7.62 and 12.7 AP projectiles, but they are much larger for 5.56-mm projectiles. Because the 5.56-mm projectile is a more deformable projectile, it consumes more energy during penetration "per unit volume," as shown in Table 6.

Table 6
Values of K/ϕ^2

Fiber dosage (kg/m^3)	Projectiles		
	5.56 × 45 mm	7.62 × 51 mm AP	12.7 × 99 mm AP
0	1.045	0.679	0.634
80	1.120	0.694	0.650

So K (average loss of kinetic energy to thickness ratio in case of total perforation) can be obtained for any projectile if we know this value for any one, in the sense discussed above, multiplying by the ratio of square calibers only. This result greatly simplifies estimation of K for a wide range of projectiles.

2.5. Study of scabbing

Even if all of the above discussion is correct, the first risk when a projectile impacts a concrete barrier are the fragments thrown out from the rear face of the barrier. This phenomenon is called scabbing. It is produced by the reflection of shock waves on the rear face of the barrier, and it will occur even before the projectile reaches the rear face.

As for the case of perforation, we can obtain an upper and a lower limit for quotients E_i/t, which cause scabbing. An upper limit will be the least value for those hits having caused scabbing or perforation, and a lower limit will be the largest value for those hits *not* having caused scabbing. These limits must be determined for each combination of projectile and quantity of fibers tested.

In Table 7 the highest and lowest values for scabbing observed experimentally are given. Values within parentheses are the same whether divided by the average value for $\Delta E/t$ or K value (Table 4). As can be seen, if fibers are added to concrete, scabbing cannot be differentiated from perforation. Without fibers, scabbing is very likely to occur with an initial kinetic energy equal to 80 to 90% of the average energy needed for perforation only.

Table 7
Upper and lower values of E_i/t for scabbing (J/cm)

Caliber	Fiber ratio	Minimum value	Maximum value
5.56	0	253 (0.79)	258 (0.80)
5.56	80	255 (0.74)	~345 (1.00)
7.62	0	285 (0.72)	360 (0.91)
7.62	80	358 (0.89)	~403 (1.00)

The risk of scabbing is normally associated with a certain penetration-to-thickness ratio. For this purpose, penetration depth, which is determined experimentally, must be measured in the normal direction to the face of the barrier. Therefore, penetration must be related to the initial kinetic energy of the projectile. This relation can be observed in Fig. 1 between penetration-to-thickness ratio and the dimensionless quotient $E_i/[t\,K]$, where E_i is the initial kinetic energy, t is the thickness of the target, and K is the average of $\Delta E/t$, supposing total perforation, which can be assumed to be constant for any combination of concrete and projectile types.

Additionally, a curve relating x/t and $E_i/[t\,K]$ appears in Fig. 3. This curve has been obtained as described below. All points are just above this curve, which is equivalent to saying that penetration is overestimated. This overestimation is due to the assumption that the path of the projectile inside the target is straight. Actually, the projectile deviates from its initial path inside the target, reducing its effective penetration. This is a favourable effect from the point of view of defence, and leaves the curve just on the safe side to avoid scabbing.

All points shown in Fig. 3 correspond to hits that have not perforated the target or produced scabbing, regardless of thickness or initial velocity. It is very important to note that the expected value of penetration-to-thickness (x/t) ratio depends on $E_i/[t\,K]$ only, regardless of projectile or concrete type: the influences of these parameters are contained in K only.

On the other hand, targets made without fibers cannot withstand a 50% penetration on their thickness without scabbing. If fibers are added, the penetration can reach 70% of thickness without scabbing. However, we have more error in estimating x/t from the quotient E_i/tK than the other way round (see Fig. 3). Therefore, the limit for scabbing is not estimated as well from kinetic energy as it is for total perforation, because the first is normally related to penetration-to-thickness ratio; but if the quotient x/t for scabbing is well known, kinetic energy for scabbing with any projectile can be calculated very accurately. To obtain a theoretical prediction of velocity effective penetration to thickness ratio, x/t is needed.

2.6. Theoretical model

Let us assume that all modes of irreversible kinetic energy dissipation can be substituted for by the work of some fictitious force, which depends of certain variables, as seen in Eq. (3):

$$f = f(x,t,v,MAT,PROJ) \tag{3}$$

where $x =$ penetration depth of projectile, in normal path to the faces of the target; $t =$ thickness of the target; and $v =$ instantaneous velocity of the projectile.

MAT and *PROJ* are those parameters of the material or the projectile affecting the force f, but that are not known either qualitatively or quantitatively. However, these parameters could be related to other parameters that are better known. In our case, these parameters are the strength of concrete, fiber dosage, and composition and structure of the projectile. A simple dimensional analysis allows us to obtain [see Eq. (4)]:

$$f = K(MAT, PROJ)\varphi\left(\frac{x}{t},\frac{v}{c}\right) \tag{4}$$

K is a parameter with force dimensions depending on variables included in MAT and PROJ; c is the velocity of shock waves inside the concrete. If the velocity of the projectile is much less than the velocity of shock waves, the fictitious force f will not depend on quotient v/c as noted above. If we also suppose that penetration is produced without loss of mass inside the target, which is possible either for a rigid projectile, or assuming that the total loss of mass is produced just on impact, the quotient $\Delta E/t$ will be theoretically independent of thickness or initial velocity of projectile, as obtained in the field. It can be seen easily that [see Eq. (5)]:

$$dE = d\left(\frac{1}{2}mv^2\right) = -K\varphi\left(\frac{x}{t}\right)dx = -tf(u)du \tag{5}$$

Changing the variable $du = d\,(x/t) = dx/t$, and integrating from $u = 0$ to $u = 1$ (total perforation), we will obtain Eq. (6):

$$\int_0^1 f(u)\,du = \frac{E_i - E_s}{t} = K \tag{6}$$

If the projectile does not perforate the target, it will suffer a deviation from its initial path inside the target, and a overestimation of penetration can be obtained from Eq. (7):

$$\int_0^{\frac{x}{t}} f(u)\,du = \frac{E_i}{t} \tag{7}$$

If the maximum value of x/t without scabbing is known, Eq. (7) will allow us to calculate the maximum velocity of the projectile to avoid scabbing. The easiest expression for $f(u)$ consistent with experimental data is shown in Eq. (8):

$$f(u) = 1.5K(1-u^2) \tag{8}$$

3. Conclusions

From experimental results we can propose a model to predict the thickness needed to avoid perforation or scabbing and to obtain the residual velocity if it perforates. The model can be valid for all massive and brittle concrete targets. The concept of "massive" is concerned with the thickness-to-caliber ratio, estimating a target as "massive" when this quotient is greater than or equal to 8 or 9. Also, the target can be assumed as homogeneous if its thickness is larger

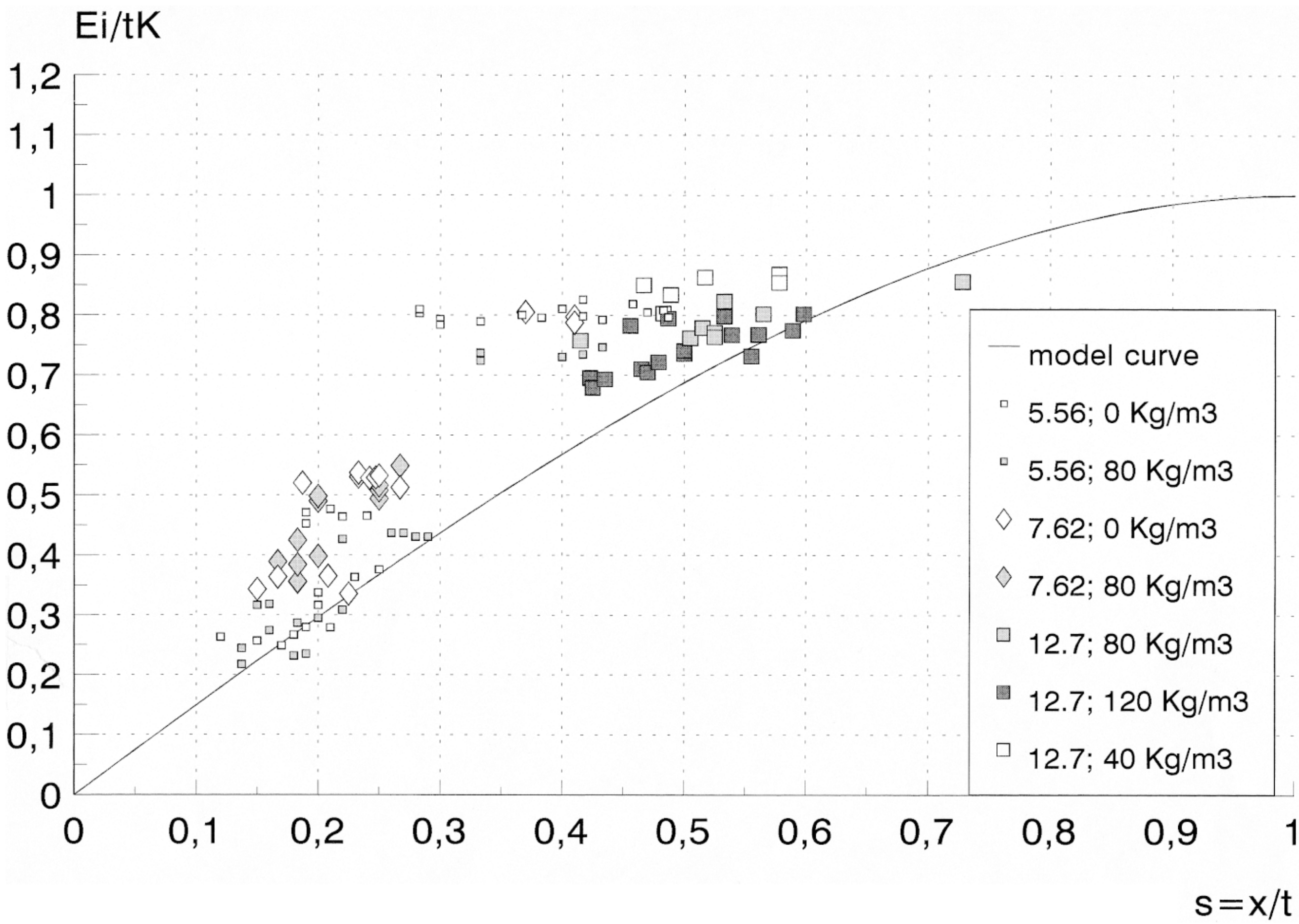

Fig. 3. Relationship between *x*/*t* and E_i/tK.

than 4 or 5 times the maximum size of aggregate. In the particular case of SFRC, the thickness must be a little bigger than the fiber length; a thickness $\geqslant 1.2 \cdot$ (fiber length) can be sufficient.

This model is based on the knowledge of the average loss of kinetic energy-to-thickness ratio K, which is assumed to be independent of thickness of the target or initial velocity of projectile. A simple scale factor has been obtained for K and between "similar" projectiles in the sense described in the text, and fired against the same type of concrete. This scale factor simplifies the calculation of K very much. In the calculation of perforation threshold thickness with some characteristic value of K, K_{cr} is recommended to obtain a conservative value. For the scabbing threshold thickness the average value of K is sufficient to obtain a safe value, because of overestimation of penetration in the model.

Fiber additions reduce only a little of the thickness needed to avoid perforation; but the thickness necessary to avoid scabbing is much smaller than that for plain concrete. Whereas for plain concrete a penetration equal to 45% or half of the thickness is sufficient to cause scabbing, this ratio must grow up to 60% when fibers are added at the rate of 80 kg/m^3.

More important is the reduction in crater volume both at the front and rear side of the target, and the capability to bear multiple hits with fiber additions, although it is more difficult to translate this to some models.

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