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Characteristics of high performance reinforced concrete barriers that resist non-deforming projectile impact

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Abstract. Current research and development of high performance concrete, together with study of phenomena that are pertinent to impact resistance, have lead to a new generation of barriers with improved properties to resist impact loads. The paper reviews major properties and mechanisms that affect impact resistance of concrete barriers as per criteria that characterize the resistance. These criteria are the perforation limit, penetration depth and the amount of front and rear face damage. From the long-known, single strength parameter that used to represent the barriers' impact resistance, more of the concrete mix ingredients are now considered to be effective in determining it. It is shown that the size and hardness of the aggregates, use of steel fibers and micro-silica have different effects on performance under impact and on the resistance. Additional pertinent phenomena, such as the rate and size effects, confinement and local versus global response, are pointed out with their reference to possible future developments in the design of impact resisting concrete barriers.

Keywords: impact; high performance concrete; penetration; fibers; aggregates.

1. Introduction

Act of extreme loading on buildings sets off structural response, which is characterized by both its local and global actions. In the case of explosive and impact loading the global behavior is mainly a result of blast overpressures, which generate dynamic response of the structural elements. Hits of fragments result in local response characterized by penetration and local damage. Barriers, which are designated to resist hard projectile impact, are implemented in both military and civil structures. Protective shelters are an obvious military or military-related application, whereas civil applications include 'sensitive' structures, such as in nuclear power plants, and mountain rock-sheds or volcanic shelters. The former civil application requires protection of vulnerable facilities against accidental impact of turbine missile or tornado-borne debris (which may also be an electric pole) and the latter involves impact of falling rocks (Mougin *et al.* 2005) or of pyroclastic eruptions (Dolce *et al.* 2007).

The structural performance and the capability to resist impact loads, makes reinforced concrete (RC) a common engineering solution in the design of protective barriers. Thus, the exterior concrete walls of a protective structure function as 'regular' structural elements that resist 'regular' gravity and live loads and as protective elements they resist fragments penetration and blast over-pressures.

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When a fragment hits such structural element it may penetrate into the element, decelerate and come to a stop or perforate it with residual velocity. Damage of the front (impact) side of the barrier includes the formation of a crater, cracking and penetration. Rear (inner, protected) side damage includes passing through of the striking fragment with residual velocity, cratering and formation of a shear plug. Even when the barrier is not perforated, rear face scabbing may develop. This phenomenon is known to be caused by tensile waves reflected from the free face of the barrier, exposing the sheltered side to strikes of concrete fragments.

Velocities of projectiles impacting concrete barriers range, in many cases, up to 1500 m/s. Within this range of impact velocities, projectiles that are made of high strength grades of steel remain virtually undeformed (Gold *et al.* 1996) while for larger striking velocities erosion of the projectiles cannot be ignored. This paper refers to the former case of non-deforming projectiles.

Until about two decades ago it was the concrete's compressive strength, f_c, which represented its resistance against impact. In fact, because f_c appears in most perforation formulas, raised to a power α, which is about ½, it essentially represents the concrete's tensile strength, where the resistance is inversely proportional to f_c^{α} (e.g., Kennedy 1976, Haldar and Hamieh 1984, Hughes 1984, Barr 1990, Williams 1994, Riera 1989). Furthermore, it has been commonly believed that there is no significant effect of relatively light reinforcement (0.3%-1.5%) on local response to impact and that within a relatively wide range of projectile diameter-to-aggregate size ratio (0.5 to 50) there is only weak influence of the aggregate size on the penetration resistance (Sliter 1980). Therefore, with the introduction of High Strength Concrete (HSC) the material's increased strength called for its use in barriers that have to resist impact. Yet the relatively increased brittleness of HSC required additional means to improve its performance, for example by the use of fibers. Application of High Performance Concrete (HPC) in laboratory tests at the Technion indeed showed promising results (Dancygier and Yankelevsky 1996, 1999). The ongoing developments of HPC have been accompanied by further study of other phenomena and mechanisms that are pertinent to impact resistance. Thus, study of the effects of confinement and rate effect on the response of RC to impact loads, combined with enhanced engineered properties of HPC are starting to introduce a new generation of barriers with improved properties to resist impact.

There are several criteria, according to which, performance and resistance of a barrier to non-deforming projectile impact should be evaluated. These are the penetration depth, front and rear face damage and Perforation Limit (PL). For a specified projectile's weight and shape, the perforation limit is evaluated either for a given barrier's thickness, in which case PL is determined by the striking velocity required for perforation (PLV or V_p), or for a given striking velocity, for which PL is determined by the thickness required to just prevent perforation (PLT or h_p). An additional criterion is the ability of a barrier to withstand multiple hits. This paper focuses on the characteristics of local response of reinforced concrete barriers to the act of non-deforming projectiles impact and reviews the major properties and mechanisms that are responsible to enhancements of the resistance as per these criteria.

2. Front face damage

2.1 Resistance criteria and influencing mechanisms

Damage to the front face of a RC barrier impacted by a projectile is characterized mainly by two parameters: the projectile's penetration depth and the size of the damaged area. Penetration depth is a common parameter used to evaluate the resistance of concrete barriers to impact. Once the depth of penetration into a semi-infinite target is calculated, most perforation formulas relate to it the thickness required to prevent rear face scabbing or perforation of the barrier. Additionally, it is important to consider the front face damaged area, which is a measure of the extent of the impact local effect. The front face damaged area is also an indirect indication of the ability of the barrier to withstand multiple hits, where a smaller damaged area indicates that larger parts of the barrier integrity are maintained. Numerous penetration tests on Normal Strength Concrete (NSC) specimens yielded the basic understanding of penetration mechanics into concrete and provided a variety of calculation methods. As mentioned above, concrete strength was considered in most penetration formulae to be the only representative property of the material, although recently there are experimental indications that concrete strength alone may not be sufficient to delineate its impact resistance (e.g., Bludau *et al.* 2006).

Concrete behavior is related also to the influences of confinement conditions and high loading rate - two phenomena, which are pertinent to the penetration process into the front face of an impacted barrier.

2.1.1 Confinement effect

The strength, as well as strain, under triaxial compression can be significantly higher and larger than those measured under uniaxial conditions. Therefore, it is likely that the state of stress at the tip of a penetrating projectile would be influenced by the level of confinement that develops around it. Several theoretical penetration models are based on the spherical cavity expansion approach (e.g., Yankelevsky 1997, Forrestal *et al.* 1994, Warren *et al.* 2004). The ability of these models to simulate the penetration process suggests that there is a considerable influence of the radial and tangential stresses around the penetrator nose on the overall resistance of the barrier and hence, that lateral confinement can have an important role in enhancing the resistance to projectile penetration into concrete. This argument is supported by the empirical findings of Sukontasukkul *et al.* (2005) who reported that under uniaxial compressive impact, the ultimate strength and corresponding strain increased with increasing confinement and that confined concrete exhibited lower secant modulus of elasticity than unconfined concrete.

Two additional and important observations made by these researchers were the higher rate sensitivity of confined concrete and the difference in the response of 'passive' and 'active' confinement (where 'passive' and 'active' confinement refer to restrained lateral deformations which result from the penetration process and from an actively applied lateral pressure, respectively): the increase in strength under passive confinement was quite small compared to the strength increase that was obtained with active confinement pressures of 0.625 and 1.25 MPa. The latter finding regarding the small sensitivity to passive confinement is also indicated by the results reported by Frew *et al.* (2006): They conducted penetration tests with three diameters of NSC concrete targets with ratios of target-to-projectile diameter of 24, 18, and 12. Although the lower ratios were likely to provide lower confinement, these test results showed negligible changes in penetration depth and only small decreases in deceleration magnitude as the target diameters were reduced. Yet, these researchers also observed more damage at the target face as the ratio of target-to-projectile diameter decreased. These findings (Sukontasukkul *et al.* 2005, Frew *et al.* 2006) indicate that active confinement, which results from an actively applied lateral pressure, is more efficient in enhancing the material properties than passive confinement, which results from the penetration process and restrained lateral deformations.

2.1.2 Rate effect

Another material property, which is strongly related to the characteristics of impact loading, is the concrete strain-rate sensitivity. Projectile impact may indeed cause high loading rate that can be high enough to affect concrete strength. Deceleration-time records that were measured during impact and reported by Frew *et al.* (2006) indicate stress rates of the order of 10^5 MPa/sec, which correspond to a lower limit of strain rate of the order of 10 s^{-1} (considering the elastic modulus of the 23-MPa concrete that was tested). The influence of loading rate on either the tensile or compressive concrete strengths, which have an effect on the impact resistance, may thus be an important factor in the design of barriers. Concrete strength increases under dynamic conditions, where the dynamic increase factor (DIF), which is used to quantify the dynamic-to-static strength ratio, is commonly described by a bi-linear function of the strain rate in a log-log plot (e.g., Malvar and Ross 1998, Weerheijm and Van Doormaal 2007): DIF in tension can reach values of 1.5 or 2 at relatively low strain rates up to 1 s^{-1} whereas a DIF of about 6 was reported for strain rates of up to 20 s^{-1} (Malvar and Ross 1998).

The influences of stress rate on the tensile and compressive strengths and on the concrete elastic modulus (compression) and fracture energy are not the same. Weerheijm and Van Doormaal (2007) reported enhancement factors of 5.3 and 1.2 for the tensile strength and the Young's modulus (respectively). They derived an upper limit for the dynamic fracture energy and concluded that its maximum enhancement factor is 2.5 at loading rates of 1000 GPa/s and that at lower rates of up to 15 GPa/s there is no increase (DIF=1). Compressive strength is also sensitive to the rate of loading but to a lesser extent. According to Reinhart (1987) and to Jensen *et al.* (1993) the DIF of the compressive strength is about 2 for strain rates of 10^1 to 10^3 s^{-1}. Sukontasukkul *et al.* (2004) measured increased values of the concrete strength, toughness and initial modulus of elasticity, under impact loading (compared to their corresponding values under static conditions). However, they also found that under impact the degradation of the concrete secant-to-initial moduli ratio is faster (i.e., it drops faster as the strain rate increases) and that the damage at the peak load is higher. Compressive strength of 40 MPa increased by a factor close to 2 whereas the initial elastic modulus increased by a factor of 4 to 12 at strain rates of about 0.2 and 0.5 s^{-1}, respectively (Sukontasukkul *et al.* 2004). Maalej *et al.* (2005) tested hybrid-fiber ECC (Engineered Cementitious Composite) and reported higher sensitivity to strain rate of this material, compared with concrete of the same compressive strength: at a strain rate of 0.2 s^{-1} they measured tensile DIF values of about 1.9 and 1.2 for hybrid-fiber ECC and concrete (respectively), compared to the static strengths measured at quasi-static rate of $2 \cdot 10^{-6}$ s^{-1}. Thus, these researchers commented, that the strain-rate effect of cementitious materials may be controlled by additional parameters other than the material's compressive strength.

2.1.3 Confinement-load rate coupling

The two effects described above - the sensitivity of the material properties to loading rate and to confinement - are not necessarily independent. In fact, there are indications that they are coupled. Li *et al.* (2003a, 2005) suggested that in Split Hopkinson Bar (SHPB) tests there is coupling between the DIF observed at high strain rates and lateral confinement, which is caused by both the contact physical restrictions of the test setup and lateral inertia of the loaded material. These researchers argued that the *compressive strength* enhancement observed at strain rates higher than 100 s^{-1} may very well be attributed to an inertial confinement effect rather than to a material property associated solely with rate effect. The combined influence of the strain-rate and confinement effects is further supported by empirical results, which showed that confined concrete exhibited higher rate sensitivity than unconfined concrete and that the ultimate strength and corresponding strain increased with increasing confinement (Sukontasukkul *et al.* 2005) as well as the material toughness and initial modulus of elasticity (Sukontasukkul *et al.* 2004). Grote *et al.* (2001) conducted experiments with small plate specimens that were confined at their perimeter. They observed that at strain rates of the order of 10^4 s^{-1} there was a significant strength enhancement and analysis of their experimental results lead them to conclude that approximately 42% of the increase in strength was due to the rate effect while 58% were attributed to the confinement effect. Zhang *et al.* (2009) have recently shown experimental evidences that further indicate how confinement induced by radial inertia has an important effect on the compressive strength DIF, obtained by SHPB tests, at strain rates that range between 10^0 to 10^3 s^{-1}. Li *et al.* (2009) used numerical simulations to analyze these experiments. Their results point at two additional parameters that may affect the compressive strength DIF: obtained by SHPB tests the geometric aspect ratio of SHPB specimens and the dynamic friction between the SHPB impacting bar and the tested concrete specimen.

Thus, higher deceleration of the penetrating projectile is expected to cause higher stress rates and therefore yield an increase of concrete resistance through increased compressive and tensile strengths and fracture energy. Hence, there is an interaction between the concrete that resists penetration and the rate at which the penetrator is resisted. However, the above studies on the strain rate effect were done on concrete specimens, either with drop-weight testing machines or in SHPB tests, and not on plate specimens under projectile impact load. Therefore the characteristics of strain rate during penetration of a slab are yet to be determined. Furthermore, as pointed out by Li *et al.* (2009), implementation in numerical simulations of DIF values of concrete compressive strength, which were obtained from SHPB tests, should be made with a careful assessment of the "real" material property (i.e., compressive DIF) opposed to phenomena that are part of the calculated response.

2.2 Penetration depth

2.2.1 Effect of concrete strength

Pilot tests, performed at Technion, that were aimed at examining the impact resistance of HSC showed increased resistance of HSC specimens compared to that of NSC (Dancygier and Yankelevsky 1996, 1999). The penetration depths that were measured at similar projectile's impact in 100 MPa concrete targets were lower than those measured in 35 MPa targets. These were tests of relatively small scale plates (40×40×5 cm^3) subjected to impact of 25-mm diameter steel projectiles.

Similar observations were obtained also in larger scale tests. Fig. 1 shows penetration depths that were measured in 80×80 cm^2, 200-mm thick, NSC and HSC plates. Noting that 'penetration' of 200 mm denotes perforation, it can be seen in Fig. 1 that the NSC plates were perforated at an impact velocity of 250 m/s. However, some of the HSC specimens, which were of similar (high) strength and were struck at velocities that ranged from 285 to 292 m/s were not perforated, but had different penetration depths. These results were taken from impact tests of specimens struck by 50-mm diameter, 1.5 kg projectiles (Dancygier *et al.* 2007). Enhanced resistance of HSC was also reported by Zhang *et al.* (2005) who measured lower penetration depths in HSC specimens than in NSC targets.

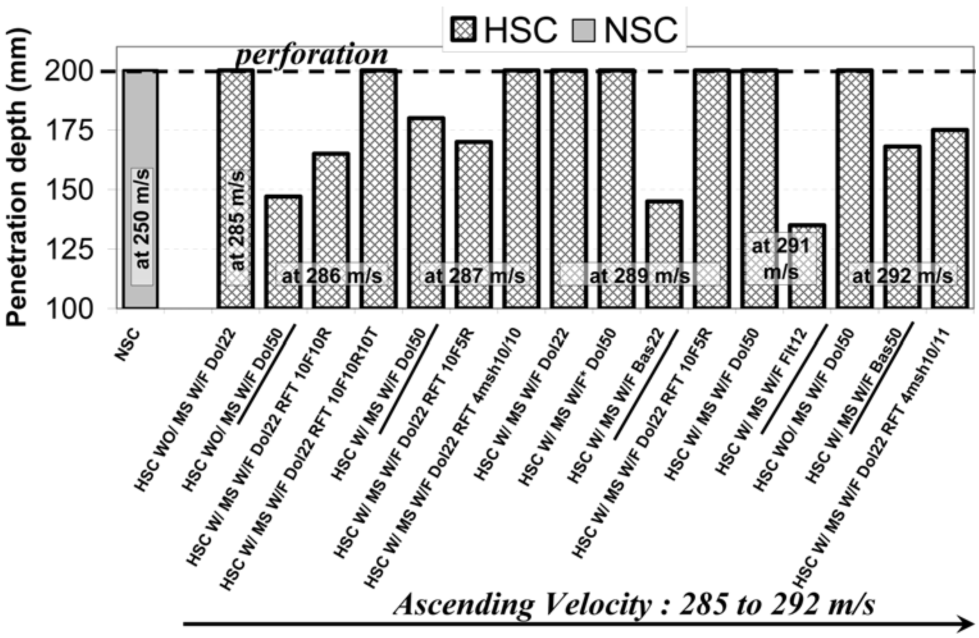

Fig. 1 Penetration depths in tests of NSC targets impacted at velocity of 250 m/s and HSC at velocity range of 285 to 292 m/s (results were taken from impact tests of 80×80×20 cm^3 specimens, Dancygier *et al.* 2007)

2.2.2 Effect of aggregate type

Frew *et al*. (1998) conducted impact tests on concrete targets that included limestone aggregates with Mohs hardness of 3.0 and compared their results with those of Forrestal *et al*. (1996) who tested concrete targets with harder, quartz-based aggregates with Mohs hardness of 7.0. Their results showed that while the aggregate hardnesses affected the amount of nose erosion, they had a small effect on the depth of penetration. However, the aggregate size in these tests was 9.5 mm whereas the projectile diameters were 20.3 and 30.5 mm. In tests conducted by Dancygier *et al*. (2007) a 50-mm diameter projectile was used with aggregate sizes of 22 and 50 mm. For these relatively larger size aggregates Fig. 1 shows that at similar HSC compressive strengths larger and harder aggregates yielded lower penetration depths (see underlined specimen-labels in Fig. 1: 'large' aggregates: 50-mm dolomite and basalt - "Dol50" and "Bas50"; 'hard' aggregates: flint - "Flt").

The influence of the aggregate size on the resistance is further supported by the experiments conducted by Zhang *et al*. (2005) and by the experimental results of Bludau *et al*. (2006) who showed that mixes with relatively large aggregates (more than twice the projectile diameter) resulted in higher resistance whereas smaller aggregates (smaller than the projectile diameter) lead to lower resistance. Analysis of experiments conducted by Grote *et al*. (2001) showed that increase of the volume fraction of the aggregates in the concrete mix caused an increase in the average stress carried by the impacted concrete and in the energy dissipation (Park *et al*. 2001). Maalej *et al*. (2005) who tested hybrid-fiber ECC noted that although ECC provided enhanced performance in reducing the front and rear damage, because of the lack of coarse aggregates the material they tested did not significantly reduce the penetration depth. Thus, the experimental results cited above indicate that resistance to penetration is affected by a mechanism, which is related to energy dissipation caused by diversion of the penetrating projectile by relatively large aggregates.

2.2.3 Projectile abrasion

Diversion of the penetrating projectile by relatively large aggregates may not be the only mechanism associated with the aggregate properties, which affects the resistance to penetration. Silling and Forrestal (2007) investigated the mass loss from abrasion on steel projectiles and found that the empirical constant that they used in their abrasion model did not depend on the projectile diameter or mass. However, their 'abrasion constant' was lower for mixes with limestone aggregates than for mixes with quartz aggregates (about 50% difference), indicating that higher abrasion is caused by harder aggregates. They also presented a table that showed that predicted penetration depths were lower and closer to the experimentally measured depths when the abrasion model was applied in their analytical model. This indicates that projectile abrasion, caused by aggregate hardness, yields higher resistance, resulting in lower penetration depths.

2.3 Size of front face damaged area

Front face damage caused by impact is characterized by formation of a crater. Part of the impacted material in front of the penetrating projectile is crushed and part of it is ejected aside, thus forming the crater. It can therefore be concluded that inhibiting these damage mechanisms would enhance the ballistic performance with regard to the penetration depth and the size of the crater. One way of achieving this is by the use of hard and large aggregates, placed in the front layer of the barrier. Fig. 2 illustrates the effect of the aggregate type, the use of steel fibers and micro-silica and of the reinforcement type on the size of the damaged area at the front face of plate specimens, tested by Dancygier *et al*. (2007). The damaged area was measured by means of an "equivalent

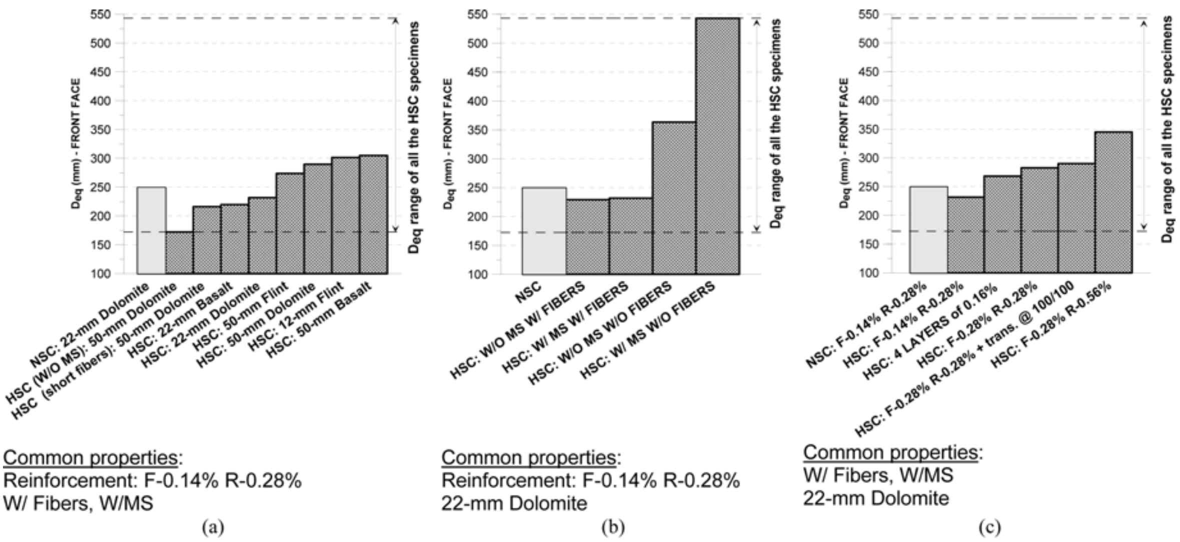

Fig. 2 Effect on front face damage of (a) aggregates, (b) micro-silica and fibers and (c) reinforcement ($80\times80\times20$ cm^3 plates; 50-mm diam. Projectiles, tested by Dancygier *et al*. (2007), at velocities close to the perforation limit. F/R-0.14%=Front/Rear reinforcement ratio of 0.14%; MS=micro-silica)

diameter" of the carter, D_{eq} (plotted in Fig. 2). It was determined from measurements of the lengths of two perpendicular axes, d_1 and d_2, which measured the longest and the shortest orthogonal dimensions of the front crater, where D_{eq} was defined as the square root of their multiplication, i.e., $D_{eq} = \sqrt{d_1 \cdot d_2}$.

Fig. 2 shows that the largest front face damaged area was caused in specimens made of concrete mixes that did not include fibers and included micro-silica. Fig. 2(b) shows that when micro-silica was not used, the same mix without fibers yielded lower front face damage (Fig. 2(b)). This result demonstrates that the increased brittleness of HSC, which can set off higher damage (compared to NSC), can be reduced by adding steel fibers. The effect of the aggregate type (size and hardness) on the front face damage is coupled with other variables, where the relatively larger dolomite aggregates yielded the lowest damage when used without micro-silica (Fig. 2(a)). As for the conventional reinforcing bars - increased reinforcement ratio near the front face did not contribute to a decrease of the equivalent front face diameter (Fig. 2(c)).

3. Perforation resistance

The ballistic limit defines the resistance against full perforation of a barrier. Together with the rear face damage (scabbing) this criterion determines the extent or level of its performance as a protective structural element. Results of impact tests showed that, as expected, higher concrete strength yielded higher perforation limit velocities, that is, higher perforation resistance (Dancygier *et al.* 1996, 1999, 2007). However, it was also found that, similarly to the effects described above on the penetration depth and front face damage, for similar compressive strengths of HSC specimens, the type and size of the aggregates had a pronounced effect on the perforation

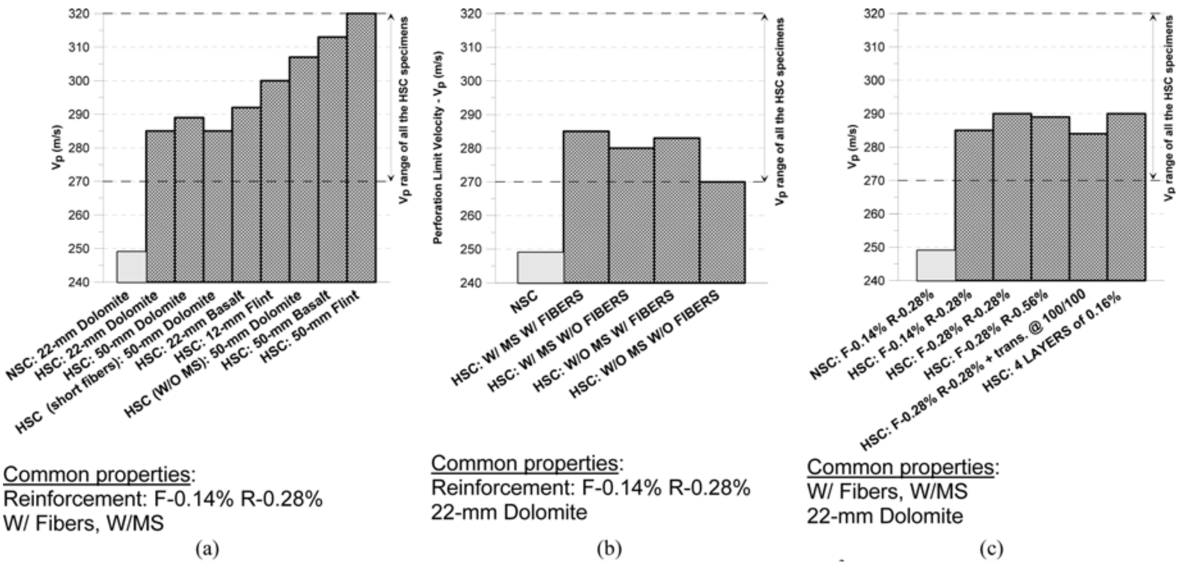

Fig. 3 Effect on perforation resistance, measured according to V_p (PLV): results of 80×80×20 cm^3 plates with 50-mm diam. Projectiles, tested by Dancygier *et al.* (2007) – effect on PLV of (a) aggregates, (b) micro-silica and fibers, and (c) reinforcement. (F/R-0.14%=Front/Rear reinforcement ratio of 0.14%; MS=micro-silica)

resistance: the harder and the larger the aggregates (compared to the projectile's diameter) the higher the resistance, e.g., for a given barrier thickness – higher PLV (Fig. 3(a)). Use of steel fibers and micro-silica also yielded increased resistance but to a lesser extent (Fig. 3(b)) and different reinforcement arrangements did not show significant influence on the perforation resistance (Fig. 3(c)).

4. Rear face damage

A significant measure of the effectiveness of a barrier to protect people and equipment sheltered behind it is the amount of damage, which develops at its rear face when struck at its front face. Rear face damage takes the form of a crater, caused by punching of the concrete, scabbing resulted by reflected tensile waves, or by both of these mechanisms (e.g., Li *et al*. 2005).

4.1 Effect of aggregate type

Similarly to the penetration resistance, it was shown that it is possible to control the amount of damage that develops in HSC barriers through their mix ingredients. This is illustrated in Fig. 4, which shows the amount of rear face damage measured in tests conducted at NBRI (Dancygier *et al.* 2007). The damage is described in the figure in terms of the equivalent diameter D_{eq} of rear craters (where D_{eq} was measured and defined in a similar way to that of the front-face damage described above). Fig. 4 and the penetration resistance described in Figs. 2 and 3 show that while larger aggregates caused higher penetration resistance at the front face, lower rear face damage was obtained when relatively smaller, 12-mm flint aggregates, were used (Fig. 4(a)). A larger size of the same types of aggregate yielded the highest perforation resistance but suffered a relatively large

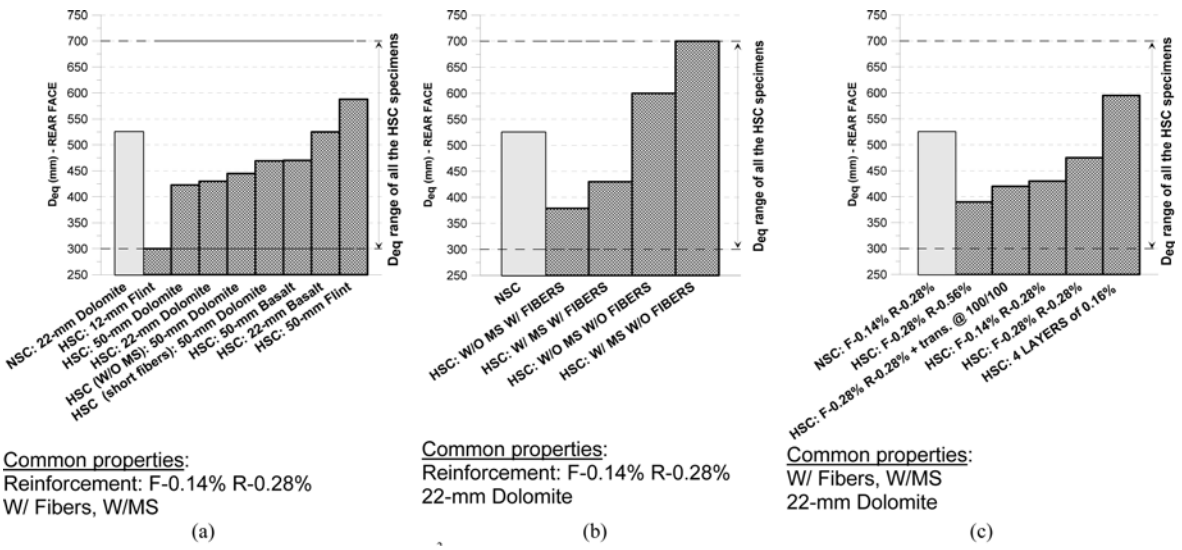

Fig. 4 Rear face damage: results of 80×80×20 cm^3 plates with 50-mm diam. Projectiles, tested by Dancygier *et al*. (2007) at velocities close to PLV – effect of (a) aggregates, (b) micro-silica and fibers and (c) reinforcement. (F/R-0.14%=Front/Rear reinforcement ratio of 0.14%; MS=micro-silica)

amount of rear face damage (Figs. 3(a) and 4(a)). This is similar to the result reported by Bludau *et al.* (2006): they tested specimens with large aggregates, which had high resistance but also large rear-face damage, whereas their specimens with smaller aggregates had relatively lower resistance but also lower damage. The mechanisms that govern these results are associated with the smaller surface area of large aggregates, which may result in lower compressive strength (Mindess *et al.* 2003, Soroka 1993) and consequently, lower bond and shear strength. Thus, while the larger size aggregates provided more volume of hard material that resisted penetration, the reduced aggregate size, which yields larger specific aggregate-matrix area, lead to higher tensile strength, and consequently, to reduced rear face damage.

4.2 Effect of silica fume and fibers

Test results of small scale, 40×40×5 cm^3 plates impacted by 25-mm diam. projectiles, showed that addition of micro-silica slightly increased the rear face damaged area whereas use of steel fibers significantly decreased it (Dancygier and Yankelevsky 1999). Fig. 4(b) shows similar response of larger scale specimens, where the smallest rear face damaged area was measured in targets that included steel fibers and did not include micro-silica whereas the largest equivalent diameter of the damaged area was developed in targets that included micro-silica but did not include fibers. Hence, the main contribution of the fibers was in reducing the damaged area. A similar result was reported by Zhang *et al.* (2005) and by Luo *et al.* (2000). Almansa and Cánovas (1999) also showed that addition of steel fibers had only a limited effect on penetration depth, yet they pointed out that use of steel fibers in their specimens decreased the thickness required to prevent scabbing and increased the capability to bear multiple hits.

Fig. 4(b) also shows that increased damage was caused by addition of micro-silica. Contrary to this effect of the micro-silica, Yan *et al.* (1999) observed a different effect in their repeated impact drop-weight tests, which were performed according to the method suggested by ACI 544 (1989) for HSC specimens. They reported that both silica fume and steel fibers can restrain HSC damage and thus increase its resistance during the process of impact, by different, complementary mechanisms. On the other hand, Dubey and Banthia (1998) conducted flexural static tests and observed that addition of silica fume increased the brittleness of the matrix and decreased the toughness of the fiber-reinforced composite, which included it. The latter result supports the experimental result described above and in Fig. 4(b).

It is interesting to note a phenomenon, which was observed in static tests, as well as in impact tests: Dubey and Banthia (1998) conducted static tests and observed that the hooked ends of steel fibers in mixes with silica-fume remained intact whereas in mixes with high-reactivity metakaolin they were straightened. Similarly, the hooked ends of steel fibers, which were added to mixes of concrete plate specimens that included silica-fume and were tested in impact (Dancygier and Yankelevsky 1999), remained intact after impacted, as shown in Fig. 5.

4.3 Effect of reinforcement

In their comprehensive review Corbett *et al.* (1996) pointed out that “the ballistic limit and failure mechanisms of concrete structures are dependant on the amount and type of reinforcement”, as opposed to what had been commonly believed (Sliter 1980). In impact tests that were done at Technion (Dancygier *et al.* 2007) it was further observed that in addition to the fibers, prudent use

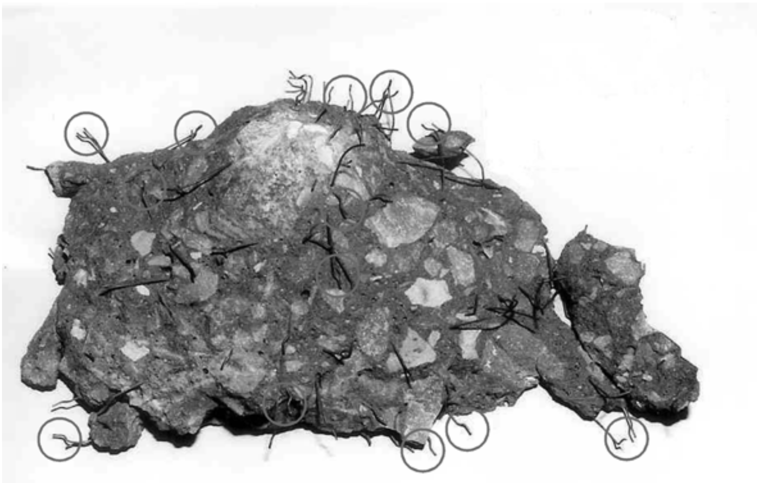

Fig. 5 Intact hooked ends of steel fibers in a piece of concrete scabbed from the rear face of impacted plate

Fig. 6 Membrane action of reinforcing mesh near the rear face (from tests done by Dancygier and Yankelevsky 1999)

of conventional reinforcement near the front and rear faces, as well as application of transverse reinforcement can reduce the amount of rear face damage. Fig. 4(c) shows that smaller damaged area was developed at the rear face of targets with similar strengths and mix ingredients when the reinforcement ratio near the rear face was doubled from 0.28% to 0.56% or when increased transverse reinforcement were applied. The action of a reinforcing mesh located near the rear face of the target is demonstrated in Fig. 6, where its membrane-like action was developed as part of the target reaction to a penetrating projectile (Dancygier and Yankelevsky 1999). Influence of the amount of conventional reinforcement on the response of lightly reinforced concrete slabs to impact of a falling weight was also observed by Zineddin and Krauthammer (2007). They reported that increase of the steel reinforcement reduced brittle damage and caused localization of the punched damaged area.

5. Additional considerations

5.1 Use of rear ballistic cover

According to the criteria used above, a barrier's performance can be enhanced by improving its ability to prevent rear face damage. In addition to the design of the mix ingredients and the reinforcement, this can be achieved by means of an external fabric attached to the rear face of the barrier. Application of fabric bonded to the concrete is mainly effective in preventing or reducing rear face damage caused by scabbing (e.g., Vossoughi *et al.* 2007). Solutions of this type should be examined also according to their influence on the functionality of the building structure in which they are to be used.

5.2 Size effect

Size effect may have an important role in concrete response, and thereby in its resistance, to penetration. Yet, it is also important to note that under impact conditions this effect may be different than the effect known under static loading because both concrete strength (NSC or HSC) and size can affect the loading rate, that is, the two phenomena are coupled. Time-dependant size-effect was reported for uniaxial compression of both NSC and HSC by Elfahal *et al.* (2005) and by Krauthammer *et al.* (2003). Frew *et al.* (2006) conducted experiments with different ratios of target-to-projectile diameters but did not measure significant differences in resistance. However, their tests were conducted with constant projectile diameter. Since concrete penetration by rigid projectiles is mainly considered as a local phenomenon, it is probably more proper to refer to the projectile diameter. For example, a measure of the impact resistance can be evaluated by the function G of the modified NDRC equation (Kennedy 1976) or by the similar, dimensionless "impact function" I, given by Li and Chen (2003),

$$I = \frac{MV^2}{d^3(S \cdot f_c)}; \quad S = 82.6 \cdot f_c^{-0.544} \tag{1}$$

Where S is a dimensionless empirical constant, which depends on the unconfined compressive strength (Forrestal *et al.* 1994, 1996, Frew *et al.* 1998) and M, V and d are the projectile's mass, velocity and diameter (respectively). Note that although S is dimensionless the coefficient 82.6 in Eq. (1) has been calibrated for values of concrete strength f_c given in units of MPa. According to Li and Chen (2003), higher values of I would yield higher penetration depths, hence lower perforation resistance. Therefore, the higher the value of I_p the lower the resistance (and vice versa), where I_p is the value of I *at the perforation limit.*

Fig. 7 shows measured values of I_p^{-1} from NSC and HSC concrete targets of "small" and "large" scale tests. "Small" scale values were taken from results of tests of 50-mm thick targets impacted by 25 mm diameter projectiles (Dancygier and Yankelevsky 1999) whereas "large" scale values were taken from tests of 200-mm thick targets struck by 50 mm diameter projectiles (Dancygier *et al.* 2007). The figure indicates a size effect phenomenon, where the projectiles with the smaller diameter yielded higher values of I_p^{-1}, hence higher resistance compared to that of the larger projectiles. It is noted that this result was obtained with ratios of the target thickness-to-projectile diameter of 2 and 4 in the tests with the small and large projectiles, respectively, which intensifies the effect of the size indicated by these results.

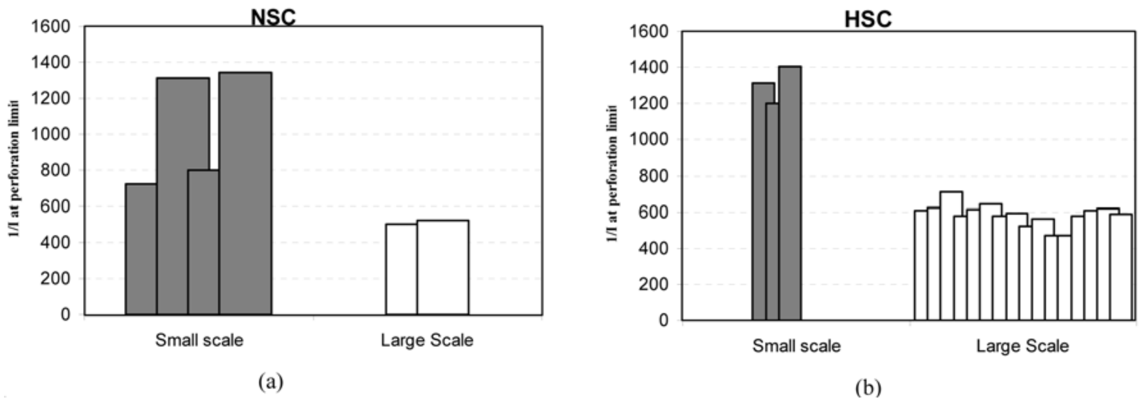

Fig. 7 Perforation resistance indicated by values of I_p^{-1} (at perforation limit), measured in experiments with 25 (small) and 50 (large) mm diameter projectiles, for (a) NSC and (b) HSC

5.3 Global vs. local response

An additional direction in the enhancement of barriers resistance to impact is the reduction of the local response. Mobilizing more of the overall, global structural response is expected to increase the impact energy required for perforation, and it could be achieved by controlling the ductility of the barrier, as indicated in the theoretical model proposed by Li *et al*. (2007).

6. Conclusions

Current research and development of HPC, accompanied by study of phenomena and mechanisms that are pertinent to impact resistance, have lead to a new generation of RC barriers with improved properties to resist impact loads. From a single concrete strength parameter that used to represent the barriers' impact resistance, more of the concrete mix ingredients are now considered to be effective in determining it. Research has shown that the size and hardness of the aggregates, use of steel fibers and micro-silica, as well as the arrangement of conventional reinforcement, have different effects on various parameters that characterize the resistance of an RC barrier and its performance under impact load. These parameters are the perforation limit, penetration depth and the amount of damage that develops at the front and rear faces. Hard and large aggregates cause higher penetration resistance at the front face but lead to relatively large amount of rear face damage whereas use of small aggregates, steel fibers and reduced amounts of micro-silica lead to lower damage. Further study should be aimed at the prudent use of this knowledge, for example, in the design of layered barriers with suitable mechanical properties according to the position of each layer in the path of a penetrating projectile.

Future study may also incorporate additional pertinent mechanisms, such as reduction of the local response by mobilizing more of the overall, global structural response, and material engineering that utilizes the rate effect and the ability to provide active confinement around the tip of an impacting penetrator.

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