Resistance of high-strength concrete to projectile impact

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ABSTRACT: This paper summarizes results from a laboratory experimental study on the resistance of concrete to simulated impact loading of fragments. The impact of fragments was simulated by the impact of ogive-nosed projectiles with a diameter of 12.6mm and a mass of 15 grams traveling at velocities from ~600 to 700 m/s. Effects of fibers, aggregate, curing temperature, compressive and flexural tensile strength of concrete on the impact resistance are evaluated and discussed. The results indicate that the incorporation of a small amount of fibers can reduce the crater diameter effectively as the fibers are able to bridge cracks and to hold concrete together. However, in order to reduce the penetration depth, reduced water-to-cement ratio and increased strength of the concrete matrix are required. Nevertheless, when the strength was beyond a certain level, further increase in the compressive strength did not reduce the penetration depth. Strong aggregate with bigger sizes seems to be beneficial to improve the impact resistance so long as the workability is satisfactory and the aggregate sizes meet requirements based on the size of structural members and the spacing between reinforcing bars and spacing between reinforcing bar and form.

1 INTRODUCTION

Terrorist attacks in recent years have led to consideration for impact resistance against blast wave and penetration of fragments for buildings and other infrastructures. For reinforced concrete structures, concrete materials subjected to impact loadings of fragments exhibit response that differ from those under static loadings. The magnitude of localized damage depends on a variety of factors such as impact velocity, mass, geometry, and material properties of the fragments, as well as the concrete properties.

When the concrete is subjected to an impact loading by fragments, a crater is usually produced as a result of the concentrated forces on the surface of the concrete. These forces are transmitted inwards, thereby crushing the concrete in the crater region. The shape and size of the crater depends on the dynamic loading as well as the strength of concrete. According to Clifton [1982], the affected area can be divided into three major regions: crater region, crushed aggregate region, and extensive cracking region (Fig. 1). In addition, scabbing may occur which is violent separation of material mass from the distal face (or opposite face) of a plate or slab subjected to an impact loading. Scabbing at the distal face occurs when the resulting wave builds up near the surface causing high tensile stresses that exceed the dynamic tensile strength of the concrete.

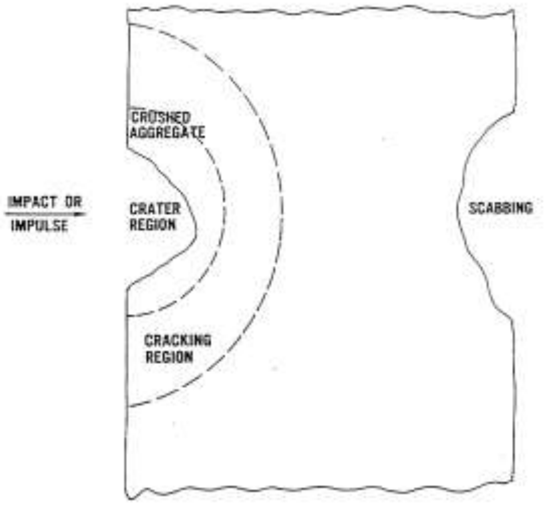

Figure 1. Fracture region in concrete subjected to an impact load [Clifton 1982]

When concrete is subjected to impact loading at high strain rates, the strength [Bachmann 1993 and Bischoff & Perry 1995] and critical strain [Bischoff & Perry 1995 and Zheng 1996] of concrete generally increase. The increase in the strength and critical strain during the high-velocity loading may be attributed to inertia effect that limits the evolution and growth of microcracks, and results in a multiple cracking phenomenon [Bischoff & Perry 1995, Weerheijm 1992, Donzé et al. 1999, and Zielinski 1982]. Experimental observations by Shockey et al. (1974), Ross et al. (1996), Li and Huang (1998), Zhao et al. (2001) show that concrete specimens fracture into a few larger fragments when loaded at low strain rates, whereas specimens break into many smaller fragments when loaded at high strain rates. The smaller fragment sizes at high strain rates indicate smaller and more cracks developed in the damaged concrete material.

Physically, the high-velocity impact loading sets up stress waves in specimens. Such loading produces a more uniform strain field because parts of the concrete material remain loaded as the wave continues to propagate through the fractured specimens. In contrast, under static loading conditions, specimens are likely to be unloaded when major cracks are formed so that no further crack can be developed. According to Li et al. [1994], a loading process of a high strain rate contains more high frequency components which activate smaller cracks in concrete than low frequency components. This leads to the concept that more cracks with smaller average sizes may be developed in concrete when subjected to loadings at high strain rates.

In normal concrete, aggregate is generally stronger with higher modulus of elasticity than cement paste. When concrete is subjected to static loadings, cracks typically pass through interface zone between the coarse aggregate and mortar matrix which is the weakest link in the concrete. At high rates of loadings, the crack path is altered due to inertia effect and cracks pass through the coarse aggregate. This also results in the increased strength.

Based on the above, a laboratory experimental study has been carried out to evaluate the influence of fibers, aggregate, curing temperature, compressive and flexural tensile strength of concrete on the resistance of concrete to simulated impact loading of fragments. This paper summarizes results and findings from the study. Details can be found in References [Zhang et al. 2005, Zhang et al. in press, and Sharif 2005]. The impact of ogive-nosed projectiles with a diameter of 12.6mm and a mass of 15 grams traveling at velocities from ~600 to 700 m/s was used to simulate the impact of fragments. Although the size and mass of the fragments may vary considerably in reality, the objective of the study is to evaluate the resistance of concrete materials subjected to such impact.

2 EXPERIMENTAL

2.1 *Testing and evaluation of impact resistance*

The experimental setup for the impact tests is shown in Figure 2. A gas gun with a 12.7 mm bore was used. The maximum attainable impact velocity was largely dependent on the mass of projectiles. In this investigation, ogive-nosed projectiles with a caliber radius head of 2.5 and a diameter of 12.6mm (Fig. 3) were used. The mass of the projectiles was approximately 15 grams. They were propelled by compressed helium at a pressure of about 150 bars to achieve impact velocities of ~600 to 700 m/s. The projectiles were fabricated from ASSAB grade 8407 supreme tool steel and hardened to 50 Rockwell Hardness Constant. After each test, the projectile was examined visually and no damage was observed. However, to ensure consistency in testing, a new projectile was used for each test.

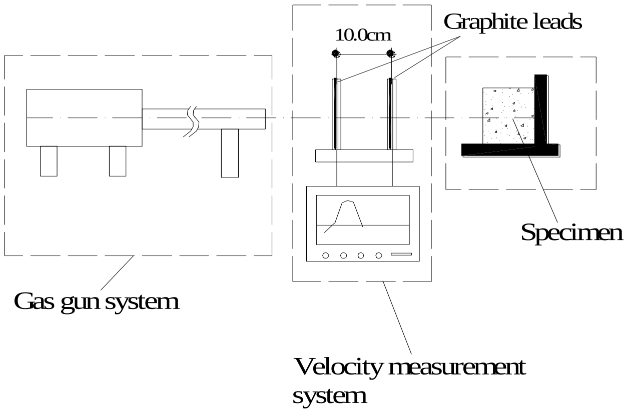

Figure 2. Schematic graph of the impact test set-up

Each test specimen was placed in a containment jig and aligned such that the projectile would hit the center of the specimen. Due to the small size of the projectile, the extent of damage caused by the impact, defined by the penetration depth and crater diameter, depended on whether the projectile struck the coarse aggregate or mortar. Therefore, in most cases, three specimens were used in the testing of each concrete mixture and the average of the results obtained was calculated. To prevent movement of the specimen during impact, two aluminum blocks were placed against the distal face of the specimen.

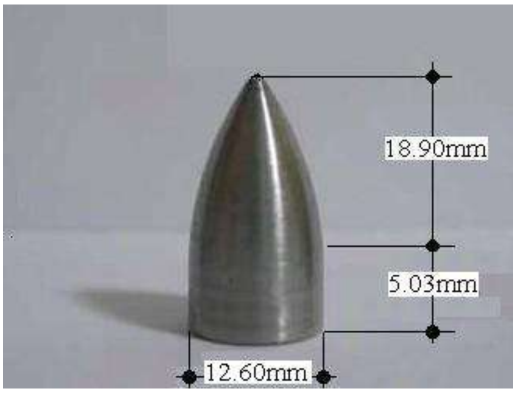

Figure 3. Projectile

Impact velocity was measured using a pair of graphite rods placed sequentially in the trajectory of the projectile just before it struck the specimen (Fig. 2). The graphite rods formed part of two electrical circuits that were connected to an oscilloscope. Sequential breakage of the rods by the projectile generated voltage changes that were recorded. By relating the time interval between the voltage changes and the distance between the rods, the impact velocity of the projectile could be calculated.

The magnitude of the impact damage induced by the impact in the concrete specimens was evaluated from the average crater diameter, maximum penetration depth, and degree of crack propagation in the specimen. The average crater diameter was determined by taking the average of four measurements, as shown in Figure 4. Penetration depth was determined by measuring the distance from the impact surface to the deepest point in the crater. The degree of crack propagation was based on qualitative observation.

The difference of the impact velocities between ~600-700 m/s was expected to affect the degree of damage. It was reported in a previous paper [Zhang et al. 2005] that the penetration depth increased with an increase in the impact velocity; however, the crater diameter appeared relatively unaffected by the impact velocity in this range. Because of this, the results of the penetration depth were normalized by dividing it by the impact velocity.

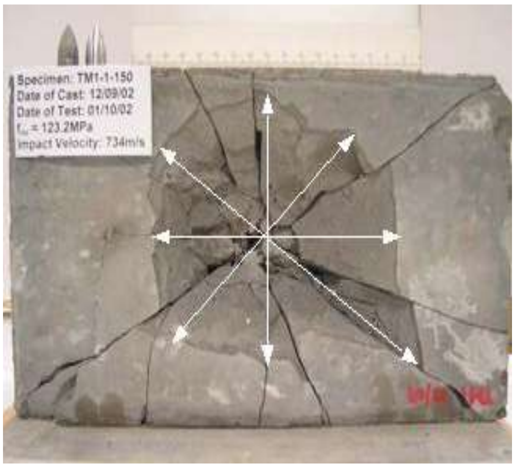

Figure 4. Determination of crater diameter.

2.2 *Concrete specimens used*

Concrete mixtures were proportioned and tested to evaluate the effects of content, type, and length of fibers, maximum size and type of aggregate, curing temperature, and concrete strengths on the impact resistance of concrete. Details of the concrete/mortar mixture proportions and materials used can be found in References [Zhang et al. 2005, Zhang et al. in press, and Sharif 2005]. The water-cementitious materials ratio (w/cm) of the concrete/mortar ranged from 0.23 to 0.55 and the corresponding compressive strength ranged from 210 to 46 MPa. Fibers with a length of 13 mm made from steel, polypropylene, and polyethylene were included in the study. Properties of the fibers are given in Table 1. The content of the steel fibers ranged from 0 to 1.5% by volume of concrete.

Table 1 – Properties of fibres used

Fibre type	Tensile strength MPa	Elastic modulus GPa	Specific gravity	Diameter, mm
Steel	2600	200	7.8	0.200
Polypropylene	30	4	0.91	0.015
polyethylene	2400	66	0.97	0.039

For most of the mixtures, the workability of concrete without fibers was controlled by slump at 50 – 100 mm and that of the fiber-reinforced concrete was controlled by Vebe test at 8-12 seconds.

Three specimens with a size of 300x170 mm and a thickness of 150 mm were prepared from each concrete mixture for the impact test. As the specimens for the impact test were relatively thick, neither perforation nor damage in the form of scabbing at their distal face was observed.

Cubes of 100x100x100 mm were also made from each concrete mixture to determine the compressive strength. In addition, prisms of 400x100x100 mm were made to determine the flexural tensile strength of concrete. For mixtures with maximum aggregate sizes < 5 mm, 50x50x50 mm cubes and 160x40x40 mm prisms were made for determining the compressive and flexural strength.

Most of the specimens were cured in moist condition at 30±2^{o} C for 7 days followed by exposure in laboratory air (30±2^{o}C) until the time of testing at 28 days except for one mixture which was cured at an elevated temperature of 250 ^{o}C.

3 RESULTS AND DISCUSSION

3.1 *Effect of fiber content*

As mentioned in the introduction, concrete specimens break into many smaller fragments when loaded at high strain rates. In order to improve the impact resistance, incorporation of fibers in concrete would be beneficial. Table 2 presents the effect of steel fiber content on the mechanical properties of concrete, penetration depth, and crater diameter on the concrete specimens subjected to the projectile impact.

Table 2. *Effect of fiber content on the normalized penetration depth (NPD) and crater diameter of the concrete subjected to the projectile impact (granite coarse aggregates, max. size = 20 mm, w/cm = 0.35)*

Mix designation	Steel fibers *%*	Strength (MPa)		Impact *V* *m/s*	Crater *D* *mm*	*NDP* x10^{-3} *mm/m/s*
		Comp	Tensile			
2NC90	0	96.9	6.0	680	104	38.3
2NCF90-0.5	0.5	112.5	7.5	701	88	34.0
2NCF90-1.0	1.0	126.7	9.8	681	82	36.2
2NCF90-1.5	1.5	123.1	9.5	663	77	34.3

The results indicated that the compressive and flexural tensile strength of the concrete increased with an increase in the fiber content up to 1.0% by volume of concrete, however, the strengths reduced slightly with a further increase in the fiber content to 1.5%. The lower strengths of the concrete with 1.5% fibers may be related to the effect of fibers on workability and thus consolidation of the concrete.

When the concrete specimen was subjected to a high velocity impact, the crater diameter and penetration depth were reduced with an increase in the fiber content. However, the reduction on the penetration depth was not significant.

Damage on the front face of the concrete specimens subjected to the projectile impact was examined after the test. Radiating cracks were observed on the control concrete specimens and concrete specimens with 0.5% steel fibers. For the specimens with 1.0 and 1.5% fibers, however, no such crack was observed except for a crater resulted from the impact by the projectile. The main beneficial effect of fibers at high rate of loadings is to bridge cracks, thereby reducing fragmentation and absorbing energy [Clifton 1982].

For steel fiber reinforced concrete in dynamic compression and tension, the energy absorbed per unit volume of concrete is proportional to the strain rate. According to a study on steel fiber reinforced concrete by Lok et al. [2003], the contribution of steel fibers to fracture toughness of concrete decreases as the strain rate increases. When a concrete specimen is subjected to the project impact, the strain rate and stress will decrease with an increase in the distance from the impact center due to the decay of stress waves. Steel fibers distant from the impact center will be more efficient to increase the toughness of concrete than that right under the impact, thus reducing crater diameter and improve the impact resistance.

From the above results, 1.0% fibers were used in concretes for evaluating the effects of fiber type and compressive and flexural tensile strength of concrete on the impact resistance.

3.2 *Effect of fiber type*

The effect of fiber type on the mechanical properties and impact resistance of concrete is presented in Table 3.

Steel fibers - The incorporation of 1% steel fibers increased the compressive and flexural tensile strengths, and impact resistance which was manifested as reduced crater diameter and penetration depth due to the impact of the projectile.

Polypropylene fibers - Compared with the steel fiber reinforced concrete, the concrete with 1% polypropylene fibers had lower compressive and flexural tensile strength and impact resistance. This is probably due to the lower strength and elastic modulus of the polypropylene fibers in comparison with the steel fibers, and poorer consolidation of the concrete as the polypropylene fibers were much finer (0.015 mm in diameter) than the steel fibers (0.20 mm in diameter).

Table 3. Effect of fiber type on the normalized penetration depth (NPD) and crater diameter of the concrete subjected to the projectile impact (granite coarse aggregates. max. size = 20 mm, w/cm = 0.35, and 1% fibers by volume of concrete)

Specimen designation	fibers types	Strength (MPa)		Impact *V* *m/s*	Crater *D* *mm*	*NDP* $x10^{-3}$ *mm/m/s*
		Comp	Tensile			
2NC90	No fiber	96.9	6.0	680	104	38.3
2NCF90-ST	steel	126.7	9.8	681	82	36.2
2NCF90-PP	PP	85.3	6.3	666	90	44.9
2NCF90-PE	PE	93.0	7.4	671	80	42.7

Note: PP= Polypropylene; PE= Polyethylene

Even compared with the control concrete without fibers, the incorporation of 1% polypropylene fibers reduced the compressive strength although the flexural tensile strength of the concrete was not affected. Under the projectile impact, the crater diameter of the concrete was reduced, but the penetration depth was increased compared with that of control concrete. The reduced compressive strength and increased penetration depth are indication of poorer consolidation of concrete due to the incorporation of the fibers.

The increase in the compressive strength due to the incorporation of steel fibers and decrease in the strength due to the incorporation of polypropylene fibers were also observed by Banthia et al. [1994]. During a low velocity impact test by Bindiganavile, et al. [2002], it was found that in general steel fiber reinforced concrete (SFRC) is tougher than the polypropylene fiber reinforced concrete (PFRC) due to the greater stiffness of steel fibers compared with polypropylene fibers. However, with the increase in the dynamic stress rate, the energy absorption capacity or toughness is increased in PFRC, whereas SFRC is increasingly brittle under impact loading. This increase in the efficiency of polypropylene fibers under impact loading is attributed to the apparent increase in its elastic modulus at high stress rates.

Polyethylene fibers - Compared with the steel fiber reinforced concrete, the concrete with 1% polyethylene fibers had lower compressive and flexural tensile strength and greater normalized penetration depth under the projectile impact, however, the crater diameter was about the same. Although the polyethylene fibers had much lower elastic modulus than the steel fibers, the tensile strength of the former is only slightly lower than the latter.

Compared with the control concrete without fibers, the incorporation of 1% polyethylene fibers increased the flexural tensile strength of the concrete. However, the compressive strength was reduced. Under the projectile impact, the crater diameter on the concrete specimen was reduced, but the penetration depth was actually increased compared with the control concrete.

Comparing the concrete with 1% of three different types of the fibers used, the performance of the concrete was in a descending order for the concrete reinforced with steel, polyethylene, and polypropylene fibers. This is probably related to the strength and elastic modulus and diameter of the fibers used. The steel fibers had the highest tensile strength and elastic modulus followed by polyethylene fibers and the polypropylene fibers. The diameter of the fibers was in the same descending order for the steel, polyethylene, and polypropylene fibers. For a given length and percentage of fibers added in concrete, the finer the fibers, the greater the number of fibers in one cubic meter of concrete. Thus, the adverse effect of the polypropylene fibers on workability of fresh concrete and thus consolidation of the concrete was probably most significant.

Short hair-line cracks radiating from the crater were observed on the specimens with 1%

propylene fibers. However, no visible crack was observed on the front face of the other fiber-reinforced concrete specimens beyond the crater.

From the discussion above, by reducing the content of the polypropylene or polyethylene fibers in concrete, the workability of the concrete may be improved so that the concrete can be consolidated more properly. This may lead to increased compressive strength and reduced penetration depth when the concrete is subjected to the projectile impact. However, reduced fiber content may lead to an increase in the crater diameter as discussed in previous section. From the results obtained, the steel fiber-reinforced concrete seems to be more suitable in resisting the projectile impact compared with the concrete with 1% polypropylene or polyethylene fibers.

3.3 *Effect of concrete strength and maximum aggregate size*

Table 4 presents the results on the mechanical properties and impact resistance of the control concrete and fiber-reinforced concrete with 1% steel fibers at different strength levels. The 28-day compressive strength of the control concrete ranged from 46.3 to 111.6 MPa (Table 4a), and that of the corresponding fiber-reinforced concrete ranged from 69.9 to 129.7 MPa (Table 4b). The incorporation of 1% steel fibers increased the compressive strength by about 15 to 50 % and increased the flexural tensile strength by about 25 to 60% compared with the corresponding control concrete.

Figure 5 shows the effect of the compressive strength on the normalized penetration depth of the concrete tested. The results clearly show that the normalized penetration depth was reduced with an increase in the compressive strength of the concrete.

Under the projectile impact, the normalized penetration depth of the control concrete was reduced by 42% with a reduction in the w/cm from 0.55 to 0.30 and an increase in the compressive strength from 46.3 to 111.6 MPa. For the fiber-reinforced concrete, the reduction on the normalized penetration depth was 35% with a reduction of the w/cm in the same range and an increase in the compressive strength from 69.9 to 129.7 MPa. However, when the strength was beyond a certain level, further increase in the compressive strength did not reduce the penetration depth. Figure 5 indicates that the normalized penetration depth is a function of compressive strength up to a certain level, and only indirectly related to the fiber content.

The effect of the compressive and flexural tensile strength on the crater diameter for the concrete tested is illustrated in Figures 6 and 7.

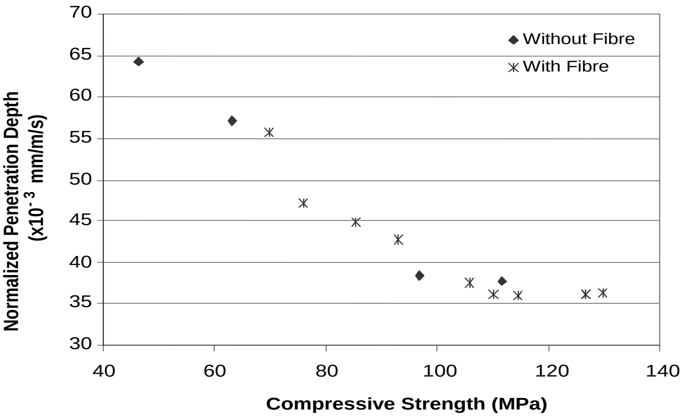

Figure 5. Effect of compressive strength on the penetration depth of the concrete specimens.

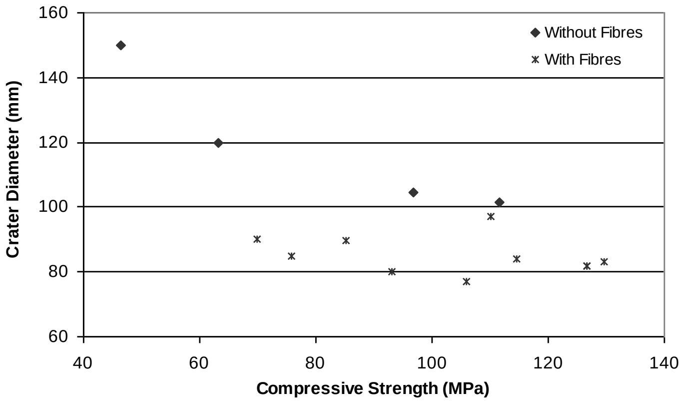

Figure 6. Effect of compressive strength on the crater diameter of the concrete specimens.

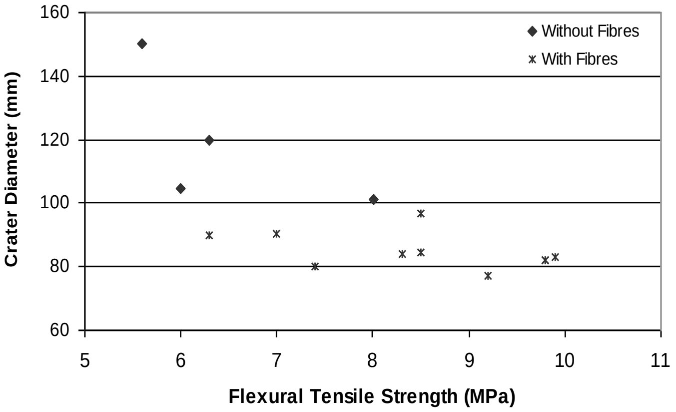

Figure 7. Effect of flexural tensile strength on the crater diameter of the concrete specimens

Table 4. Effect of the compressive strength on the penetration depth and crater diameter of the concrete subjected to the projectile impact

Specimen	w/cm	Steel fibers, % by vol. of concrete	Type of aggregate / max size	Compre-ssive strength, MPa	Flexural tensile strength, MPa	Impact velocity (m/s)	Crater Diameter, mm	Normalized penetration depth,x10^{-3} mm/m/s
2NC40	0.55	0	Granite/ 20mm	46.3	5.6	669	150	64.3
2NCF40		1.0		69.9	7.0	690	90	55.6
2NC60	0.45	0	Granite/ 20mm	63.3	6.3	632	120	57.0
2NCF60		1.0		75.9	8.5	679	85	47.2
2NC90	0.35	0	Granite/ 20mm	96.9	6.0	690	104	38.3
2NCF90		1.0		126.7	9.8	681	82	36.2
2NC120	0.30	0	Granite/ 10mm	111.6	8.0	677	101	37.6
2NCF120		1.0		129.7	9.9	698	81	36.3
Granite	-	-	-	185	-	649	34	17.4

For the control concrete, the increase in the compressive and flexural tensile strength resulted in reduction in the crater diameter. For example, the crater diameter of the control concrete was reduced by 33% with a reduction in the w/cm from 0.55 to 0.30 and an increase in the compressive strength from 46.3 to 111.6 MPa. For the fiber-reinforced concrete, however, the increase in the strengths did not reduce the crater diameter significantly. From Figures 6 and 7, it is clear that the crater diameter may be significantly reduced with the fibers even at the same strength level. The crater diameter of the steel fiber-reinforced concrete with a w/cm of 0.55 and a compressive strength of 69.9 MPa was lower than that of the control concrete with a w/cm of 0.30 and a compressive strength of 111.6 MPa.

In addition to the above, a mortar with 28-day compressive strength of 173.8 MPa and flexural tensile strength of 25.4 MPa was made and evaluated on its impact resistance. The purpose of including the mortar was to evaluate the effect of coarse aggregate and therefore maximum aggregate size in concrete on the impact resistance. The high strength was achieved by reducing w/cm to 0.23 and using granite aggregate with maximum size of 5 mm. The purpose of using smaller maximum aggregate was to reduce heterogeneity and stress concentration between phases when the concrete is subjected to loading. The mortar included 1.5% steel fibers (13 mm in length). Under the projectile impact, the average crater diameter of three specimens was 76 mm, only slightly lower than those of the fiber-reinforced concrete with the compressive strength of around 125 MPa (Mixes 2NCF90 and 2NCF120). However, the normalized penetration depth was 45.9 x 10^{-3} mm/m/s, higher than those on the concrete specimens 2NCF90 and 2NCF120. This may be attributed to the smaller size of the aggregate used in this mortar mixture.

Under the impact loading, rapid increase in stress in the concrete specimens may drive cracks into rapid extension. These cracks may be forced to propagate through the coarse aggregate rather than around them. Since granite is formed from solidification of molten rock matter, the aggregate derived from granite is generally stronger than the cement paste. Table 4 shows that the average normalized penetration depth on three granite specimens was only 17.4 x 10^{-3} mm/m/s determined by the same test method. This was much lower than those for the high-strength concrete presented in the same table. This suggests that the larger granite aggregate particles may act as barriers to the penetration of the projectile and to crack propagation.

The dynamic behavior of concrete subjected to the impact by a projectile is complex. It is believed that high compressive stresses are exerted by the projectile tip on the concrete, whereas high tensile stresses generated by stress wave and shear stresses generated by projectile penetration are induced at the circumference in the concrete specimens. In order to reduce the crater diameter effectively, the incorporation of a small amount of fibers in concrete is required as the fibers were able to bridge cracks and to hold concrete together. However, to reduce the penetration depth, reduced water-to-cement ratio and increased strength of the concrete matrix is required. Strong aggregate with bigger size seems to be beneficial to improve the impact resistance so long as the workability is satisfactory and the aggregate size meets requirements based on the size of structural members and the spacing between reinforcing bars and spacing between reinforcing bar and formwork.

3.4 *Effect of curing temperature*

Since granite has better impact resistance than high-strength concrete, the impact resistance of the concrete may be enhanced by improving the cement paste. Generally, the strength of the cement paste may be improved either by reducing the w/cm ratio and porosity, or by changing the nature of the hydration reaction products.

Table 5. Effect of the curing temperature on the normalized penetration depth (NPD) and crater diameter of mortar* (1.5% steel fibers by volume of mortar, w/cm=0.23, graded quartz aggregate with a maximum size 1.18mm was used instead of normal sand)

Speci-men	Curing T, °C	Strength (MPa)		Impact V m/s	Crater D mm	NDP $x10^{-3}$ mm/m/s
		Comp	Tensile			
QFF-30	30	187.2	31.5	681	75.8	53.5
QOF	250	203.5	32.8	641	84.0	51.0

* Workability not controlled by Vebe time. However, the mortar was sufficiently workable for casting. Compressive strength determined by 50x50x50-mm cubes, and flexural tensile strength determined by 40x40x160-mm prisms.

From laboratory tests, the w/cm can be reduced to ~0.20 without significantly affecting the consolidation. However, beyond this, workability would be reduced to the extent that the concrete may have a higher porosity and lower strength because of difficulty in consolidation. Therefore, the effect of high temperature curing was studied to determine if a change in the nature of the hydration reaction products would affect concrete strength and impact resistance. According to Richard et al. [1995], curing cement pastes at 250°C result in the formation of crystalline calcium silicate hydrate xonolite C_6S_6H, which differs from generally amorphous calcium silicate hydrates formed in cement pastes cured at room temperatures. They attributed the improved strength of the cement paste cured at 250°C to the formation of crystalline calcium silicate hydrates.

The effect of curing temperature on the strengths and impact resistance of the mixtures with a w/cm of 0.23 is presented in Table 5. An increase in curing temperature from 30 to 250°C increased the compressive strength by about 9%, but had no significant improvement on the flexural tensile strength and impact resistance. No visible cracking outside the crater region was observed for specimens cured at 30°C. However, short hair-line cracks radiating from the crater were observed in one of the three specimens cured at 250°C.

4 SUMMARY & CONCLUSIONS

Based on the results and discussion, the following conclusions may be drawn:

1. The crater diameter and penetration depth were reduced with an increase in fiber content up to a level of which workability and consolidation of concrete are not adversely affected by the fibers. However, the reduction on the penetration depth was not significant.
2. The concrete with 1% steel fibers seem to be more suitable in resisting the projectile impact compared with the concrete with 1% polyethylene or 1% polypropylene fibers.
3. The penetration depth was reduced with an increase in the compressive strength of the concrete. However, when the strength was beyond a certain level, further increase in the compressive strength did not reduce the penetration depth. The penetration depth is a function of compressive strength of concrete up to a certain level, and only indirectly related to the fiber content. For the control concrete, the increase in the compressive and flexural tensile strength resulted in reduction in the crater diameter. For the fiber-reinforced concrete, however, the increase in the strengths did not reduce the crater diameter significantly. The

crater diameter may be significantly reduced with the fibers even at the same strength level.

4 The granite specimens exhibited better impact resistance compared with the high-strength concrete. Aggregate seems to have significant effect on the penetration depth and crater diameter in concrete under the projectile impact.

5 An increase in the curing temperature from 30 to 250^{o}C did not influence the impact resistance of concrete significantly.

In summary, in order to reduce the crater diameter effectively, the incorporation of a small amount of fibers in concrete is beneficial as the fibers were able to bridge cracks and to hold concrete together. However, to reduce the penetration depth, reduced water-cement ratio and increased strength of the concrete matrix is required. Stronger aggregate with bigger sizes seem to be beneficial to improve the impact resistance so long as the workability is satisfactory and the aggregate sizes meet requirements based on the size of structural members and the spacing between reinforcing bars and spacing between reinforcing bar and formwork.

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