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The influence of steel fibre reinforcement on the ballistic resistance of concrete

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This study involves research on the influence of steel fibre reinforcement on the ballistic resistance of concrete. Concrete panels were cast with varying thicknesses and fibre volumes and subjected to a kinetic energy related ballistic attack. A .30-'06 hunting rifle using specially loaded ammunition was used to simulate the kinetic energy of ballistic attacks performed by an AK-47. The failure mechanism has been identified to consist of the Crater and Crushed Aggregate regions which are dependent on the Compressive Strength of the concrete and the Scab region, which is dependent on the Tensile Strength of the concrete. The ballistic resistance of the concrete panels was determined by taking volumetric measurements of the failure regions. Ultrasonic Pulse Velocity tests were conducted to determine the crack formation and propagation caused by the ballistic attacks. By incorporating the use of steel fibres, the Compressive and Tensile Strength of the concrete panels were improved which led to an increase in ballistic resistance of the concrete panels as well as an increase in damage mitigation. It has also been found that an increase in the thickness of the concrete panels led to an increase in overall ballistic resistance of the concrete panels.

Keywords: Concrete Ballistics, Fibre Reinforcement, Impact Testing

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This study involves research on the influence of steel fibre reinforcement on the ballistic resistance of concrete. Concrete panels were cast with varying thicknesses and fibre volumes and subjected to a kinetic energy related ballistic attack. A .30-'06 hunting rifle using specially loaded ammunition was used to simulate the kinetic energy of ballistic attacks performed by an AK-47. The failure mechanism has been identified to consist of the Crater and Crushed Aggregate regions which are dependent on the Compressive Strength of the concrete and the Scab region, which is dependent on the Tensile Strength of the concrete. The ballistic resistance of the concrete panels was determined by taking volumetric measurements of the failure regions. Ultrasonic Pulse Velocity tests were conducted to determine the crack formation and propagation caused by the ballistic attacks. By incorporating the use of steel fibres, the Compressive and Tensile Strength of the concrete panels were improved which led to an increase in ballistic resistance of the concrete panels as well as an increase in damage mitigation. It has also been found that an increase in the thickness of the concrete panels led to an increase in overall ballistic resistance of the concrete panels.

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1. INTRODUCTION

"Sweat saves blood" – Erwin Rommel.

Radicalized terrorist groups have become a problem as of late. These groups target the civilian population with mass shootings and explosives. It is therefore important to design and construct infrastructure to protect those who may be a target. Some countries experience a high crime rate consisting of criminal activities that includes gun related violence with drive-by shootings as an example. These activities influence the lives of innocent civilians and lives may be lost. It is thus important to find building materials that can withstand impact loading by absorbing energy without shattering under impact. Unreinforced concrete is normally deemed to be brittle, and it is known that steel fibres can be added to concrete mixtures to improve ductility and increase absorption before fracture [1].

There are existing standards for the development and standardization of ballistic protection, for both vehicles and body armour. NIJ [2], Alpineco [3] and NATO's STANAG [4] are but a few of the standards specifying the standardization of ballistic armouring, but none of them include the standardization, development and applications for the ballistic resistance of concrete. Although extensive research has been conducted on the impact resistance of concrete [1, 5-10, 12, 13], only limited design guidelines have been developed that can be used to design concrete exposed to high impact loading.

In this study, the effect of steel fibre reinforcement on the ballistic resistance of concrete was investigated. The study is of experimental nature. Research was conducted on the failure mechanism of concrete under high velocity impacts and the material properties that were sought after to increase the ballistic resistance of concrete, such as an increase of both compressive and tensile strengths. Experiments were set up and performed in order to determine any significant performance improvements of the concrete panels. The experiments were divided into two groups, the first comprised of a range of tests to determine the material properties of the concrete used to construct the panels and the second, to determine the ballistic performance and resistance of the concrete panels. The results were analysed, and various conclusions have been reached regarding the relationships between the material properties of the concrete and the ballistic resistance that the panels provided.

2. FAILURE MECHANISM OF CONCRETE UNDER HIGH VELOCITY IMPACTS

When a projectile traveling at a high velocity impacts a concrete target, it induces a longitudinal compressive wave. Depending on the thickness of the concrete, the compressive wave reflects back as a tensile wave once it hits the unconfined face at the back of the target. If the amplitude of this tensile wave exceeds the tensile strength of the concrete, it forms cracks in the concrete and propagate existing cracks [9].

The failure mechanism of concrete under high velocity impacts can be divided into three regions [9], as illustrated in Figure 1. The first region is the crater and crushed aggregate region. This region is dependent on the compressive strength of the concrete. Literature has shown that the crater is of conical shape and the volume of the crater is inversely proportional to the square root of the compressive strength [10]. The second region is the cracking region, which is dependent on the tensile strength of the concrete. The third region is the scab region. Scabbing is the loss of material at the back of the concrete target. This region is dependent on the tensile strength as well as the thickness of the concrete target. Due to the dependency of the scab region on the thickness of the concrete target, it may or may not occur. If the concrete target is of sufficient thickness, the longitudinal wave induced by the impact may dissipate and scabbing will not occur.

It is important to now clarify the definition of perforation. If the velocity of the projectile is such that it penetrates the target and the tip of the projectile protrudes from the back of the target, or the projectile leaves a hole such that light can shine through, the velocity of the projectile meets the U.S. Army's criterion for perforation [11]. If the velocity of the projectile enables it to pass through the target but has no energy, the velocity of the projectile meets the U.S. Navy's criterion of perforation [11]. The use of the above-mentioned definitions for perforation depends solely on the practical application of the target. For the purpose of the study, the U.S. Army's criterion for perforation will be used.

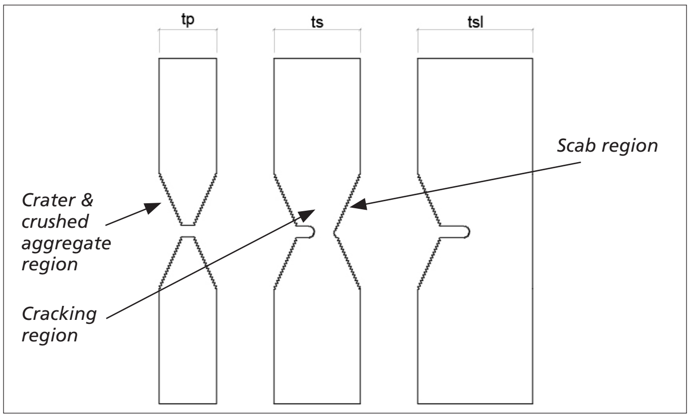


Figure 1: Failure Mechanism of Concrete Under High Velocity Impacts [10]

Various thickness definitions may be given to the concrete target, which consists of combinations of the three regions of the failure mechanisms as well as referring to perforation [12]. The Perforation Thickness (t_p) may be defined as the maximum thickness at which a projectile will perforate the target. All three failure regions are found in the Perforation Thickness, where the crater and scab regions may be directly linked together (given that the target is thin enough) or they may be connected via a "tunnel" caused by the penetration of the projectile. An increase in thickness leads to the Scabbing Thickness (t_s), which is the minimum thickness at which scabbing occurs without perforation taking place. An increase in thickness surpassing the Scabbing Thickness leads to the Scabbing Limit Thickness (t_{SL}). This is the minimum thickness of the target to prevent scabbing from occurring.

3. MIX DESIGN AND MATERIAL PROPERTIES

The mix design consisted of a CEM II 52.5N Portland Cement, Undensified Silica Fume, Fly Ash, Ground Granulated Blast Furnace Slag, Dolomite sand (< 4.5 mm), Dolomite stone (< 9.5 mm), Spring Steel Micro Fibres, Polypropylene Fibres and CHRYSO OPTIMA 100 Superplastisizer. A water-cement ratio of 0.4 was used. Spring Steel Micro Fibres with 2500 MPa tensile strength, 13 mm in length, 0.2 mm in diameter and aspect ratio of 65 were used. The amount of steel fibres varied for four different mixes. Mix 1, the control, had 0.0% fibres, whereas mixes 2, 3 and 4, contained 1.5%, 3.0% and 4.5% fibres respectively, with relation to volume. Polypropylene fibres were added to the mix to reduce the amount of initial shrinkage cracks that could propagate further during the ballistic testing. The mixing, casting and curing took place in the Civil Engineering Laboratory of the University of Pretoria. Table 1 contains the material properties of the various mix designs and Table 2 contain the respective standard deviations. The compressive strength as indicated in Table 1 is the average 28-day water cured strength obtained from three 100 mm cubes while the indirect tensile strength was obtained from four split cylinder tests conducted on 100 mm diameter cylinders. The direct tensile strength was taken from the average of 3 prisms in the shape of a "dog-bone" with a square cross-section of 50 mm sides. The "dog-bones" were pulled along the longitudinal axis until failure occurred. The direct tensile test also indicated that the failure mechanism of the fibres within the concrete matrix was of shear failure where the fibres pulled out of the matrix instead of fracturing. This was due to a weak bond-strength and indicated that the full tensile potential of the fibres was not utilised. The modulus of elasticity was determined by taking the average of measurements from two cylinders, 200 mm in length and 100 mm in diameter, cured for 28-days.

Table 1: Summary of Material Properties

Fibre Percentage [%]	Compressive Strength [MPa]	Tensile Strength [MPa]		Modulus of Elasticity [GPa]
		Direct	Indirect	
0.0	78.3	3.5	4.9	33
1.5	103.8	4.7	9.7	37
3.0	114.6	5.9	13	44
4.5	115.3	7.2	14	41

Table 2: Standard deviations of Material Properties

Fibre Percentage [%]	Compressive Strength [MPa]	Tensile Strength [MPa]		Modulus of Elasticity [GPa]
		Direct	Indirect	
0.0	4.22	0.40	0.34	0.71
1.5	6.56	0.56	0.17	0.62
3.0	5.55	0.32	0.88	1.05
4.5	2.79	0.39	0.49	1.60

4. BALLISTIC TESTING AND RESULTS

The ballistic testing was performed at the Bluegum Valley Shooting Range located near Bronkhorstspruit. It is an outdoor shooting range located within a plantation. The trees of the plantation as well as the embankments situated on the sides provide for excellent wind protection.

The targets were placed 20 m from the firing station and velocity measurements were taken at 10 m from the target. The method of exponential decay, shown in equation 1, was used to calculate the impact velocity of the projectile, assuming a constant drag coefficient, C_d, of 0.33 with υ_I as the impact velocity [m/s], υ_X the velocity at point of measurement [m/s], X as the distance from the target [m], ρ_{air} the density of air at standard conditions (1.225 kg/m^3), m as the mass of the projectile [kg] and d as the projectile diameter [m]. The mean projectile mass was 9.23 g reaching an impact velocity of 780 m/s, producing 2 808 J of kinetic energy.

$$\upsilon_I = \upsilon_X * e^{\frac{-X*\rho_{air}*\pi*C_d*d^2}{8m}} \qquad \text{Equation (1)}$$

The firing station consisted of an elevated table and the rifle, a .30-'06 SAKO, was propped up with a special sandbag used for precision shooting. The rifle has a 1:12 twist rate. A Prochrone Chronometer was used for velocity measurements as shown in Figure 2 (a). A steel frame was constructed to hold the concrete panels in a fixed position. Pieces of threaded rod were used to screw the panels tightly in place. The threaded rods, however, did not screw directly to the concrete panels. Pieces of flat bar were used to distribute the forces evenly. The influence of the addition of steel fibre reinforcement with respect to the ballistic resistance of concrete panels is clearly illustrated in Figure 2 (b), (c). The unreinforced concrete panel was completely destroyed due to its brittle nature.

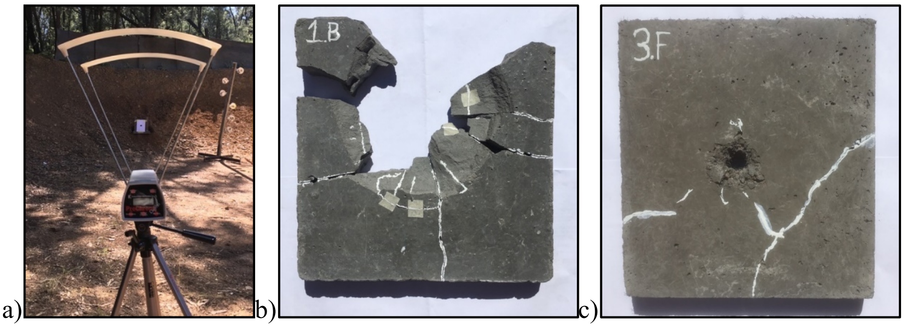


Figure 2: a) Prochrono chronometer, b) unreinforced concrete panel, c) fibre reinforced concrete panel

The following measurements were taken in order to gauge the ballistic performance of the fibre reinforced concrete panels: crater diameter and volume, perforation percentage and the Ultrasonic Pulse Velocity over the thickness of the panel both before and after being subjected to ballistic attack.

When examining the crater inflicted by the projectile, a general trend can be found. It can be seen in Figure 3 that for both the diameter and the volume of the crater, a decrease in size occurs with an increase in the percentage volume of steel fibres. It can also be seen from the same graphs in Figure 3, that with an increase in compressive strength, a decrease in crater diameter and volume occurs. This confirms that the crater and crushed aggregate region is indeed dependent on the compressive strength of the mix, as stated in the literature. When examining the crater diameter alone, it can be seen that the 50 mm panel experienced the least amount of damage. This is due to the 100% perforation that occurred for mixes 1 and 2 containing 0.0% and 1.5% volume steel fibres respectively, as can be seen in Figure 3. With 100% perforation, the projectile leaves the panel with residual velocity and therefore the panel has less kinetic energy to absorb. With mixes 3 and 4 containing 3.0% and 4.5% volume of fibres, an increase in compressive strength occurred. In conjunction with the increase of compressive strength, the increase of volume of fibres lead to the formation of a mesh that enabled the panel to capture the projectile, thus resulting in perforation percentages less than 100%.

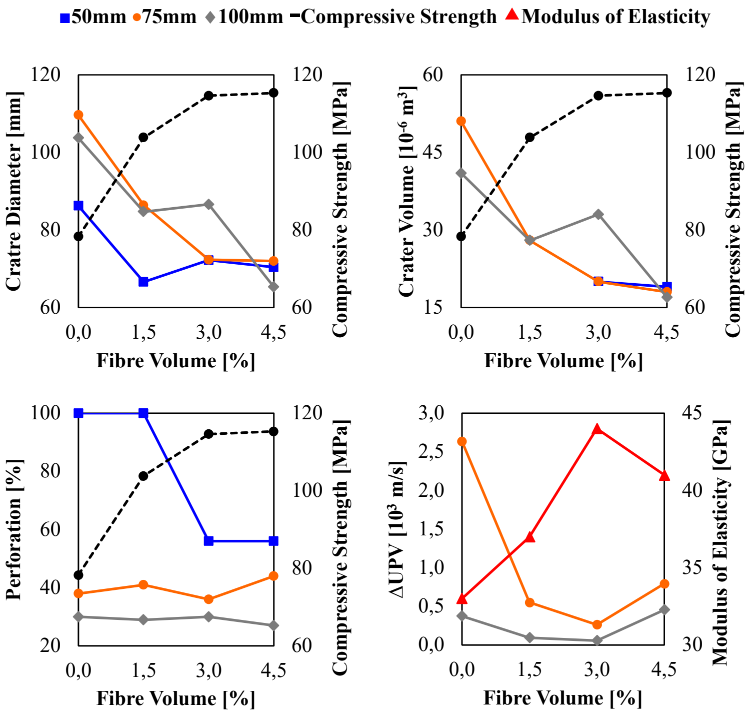
When examining the 75 mm and 100 mm panels, both a decrease in crater diameter and volume occurred. This is due not only to the increase in both compressive strength and volume of fibres, but also due to the increase in thickness of the panels. An increase in the thickness leads to an increase in the energy absorption capability of the panels, due to the increased longitudinal wave dissipation that occurs.

Lastly, regarding the perforation percentage, panel thickness and compressive strength, it can be seen that for the thicker panels (75 mm and 100 mm) that neither the fibre percentage nor the compressive strength of the mixes have a significant effect on the perforation percentage. When concrete is subjected to high strain-rates, it experiences an increase of compressive strength [13]. This is caused by the combination of the lateral inertial confinement effect as well as material behaviour. This increase of compressive strength can be quantified by the Dynamic Increase Factor (DIF) and is dependent on aggregate properties and specimen size [13]. Therefore, an increase in specimen size will cause an increase in the DIF which results in a decrease in perforation percentage.

When examining the thinner panel (50 mm) in this regard it can be seen that a significant increase in compressive strength occurs with the addition of 1.5% volume fibres, but no decrease in perforation percentage occurs. When the volume of fibres was increased from 1.5% to 3.0%, a slight increase in compression strength occurred, but a significant reduction in the perforation percentage occurred. This suggests that the quasi-static compressive strength does not play a role in the perforation percentage of the concrete panels, but rather the volume of fibres present in the mix and the thickness of the panels. The explanation for this is the combination of the longitudinal wave dispersion that occurs as well as the mesh-formation that is provided from the fibres.

When considering the ultrasonic pulse velocity of the panels it can be seen from Figure 3 that after the ballistic attack, a general decrease in the difference in ultrasonic pulse velocity, ΔUPV, (from before being subjected to ballistic attacks) occurs with an increase in volume of fibres in the mixes. When examining the 75 mm and 100 mm panels, it can be noted that there is a slight increase in ΔUPV from 3.0% to 4.5% volume fibres. This is due to dispersion problems of the fibres within the matrix. Voids are formed within the matrix which increase the readings obtained from the ultrasonic pulse velocity tests. Furthermore, an increase in the modulus of elasticity occurs with the addition of fibres but tapers down from 3.0% to 4.5% volume fibres. This is due to dispersion problems of the fibres.

When observing the significant increase in modulus of elasticity that occurs with the fibre volume increase from 1.5% to 3.0%, it can be seen that the ΔUPV reading remains almost constant for the 100 mm panel and only decreases slightly for the 75 mm panel. This indicates that the modulus of elasticity is a weak indicator of the energy absorption capabilities of the concrete panels under high velocity ballistic attacks and that the volume of fibres yet again has the greatest effect. The ultrasonic pulse velocity readings of the 50 mm panels were neglected due to unreliable readings which was caused by the increase in damage experienced by the panels during the ballistic attacks.



5. CONCLUSIONS

It can be concluded that an increase in the volume of fibres in this specific concrete mix contributes to a positive influence on the material properties beneficial to the ballistic resistance of the concrete panels. An increase in the volume of fibres resulted in an increase in the compressive and tensile (both direct and indirect) strengths of the concrete mix. This led to a decrease in crater diameter and volume as well as penetration depth. It should be noted that a fibre volume saturation point was reached in the vicinity of 4.5% volume fibres. An increase in fibre volume past this saturation point will lead to a decrease in strength and ballistic resistance. An increase in the volume of fibres also contributed to an increase in damage mitigation of the concrete panels (i.e., crack formation and propagation), as can be seen from the results of the ultrasonic pulse velocity tests.

It was also found that the ballistic resistance of the concrete panels is dependent on the thickness of the panels. An increase in the thickness of the panels lead to better dissipation of the shockwave induced by the impact of the projectile. This increase of shockwave dissipation resulted in less damage occurring in terms of volume loss as well as in the formation and propagation of cracks in the concrete surrounding the point of impact.

It can be concluded that the crater diameter and volume are indeed dependent on the compressive strength of the concrete panels as suggested by the literature. The perforation percentage of thicker panels (75 mm and 100 mm) is solely dependent on the thickness of the panels and is not affected by the volume of fibre and compressive strength. The perforation percentage of thinner (50 mm) panels is dependent on the volume of fibres and not the compressive strength. Finally, the volume of fibres in the concrete panels have a greater contribution to energy absorption and damage mitigation than the modulus of elasticity. **CB**

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