University of Southern Queensland

Faculty of Engineering and Sciences – School of Engineering

Feasibility of Blast Walls Constructed with Normal Strength Fibre-Reinforced Concrete

A research paper submitted by

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University of Southern Queensland

School of Engineering

ENP4111 Dissertation Project

(This is a 2-unit research project in Bachelor of Engineering Honours Program)

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Abstract

***Keywords**: Civil, Ballistic Performance, fibre reinforced concrete*

The world is constantly experiencing conflicts where explosives and forward firing weapons will pose a threat to important infrastructure, military assets and civilians in major cities and fringe territories. Where such elements cannot be moved to a safe location, spatially separated or within a conflict zone, blast walls systems can be erected to shield and protect what lays behind from blast waves and high energy projectiles, whether that be fired from a weapon system or fragmentation from an explosion.

This research aims to undertake a feasibility study on the effectiveness of normal strength fibre reinforced concrete with a comparison to normal strength non-fibre reinforced concrete. Both blast and projectile events can be accidental, deliberate or through indirect action, especially in the military context where aircraft weapons are accidentally fired on ground or in hangars. Due to the safety critical nature of blast walls and the level of protection required, extensive research has been conducted on blast walls constructed with high performance, yet very expensive and exotic materials. Some Countries and groups may not have the finance and resources available for top-end solutions, so this project seeks to explore the feasibility of blast walls constructed with more common materials.

The scope of this research project is restricted to 5.56 mm small arms ammunition for the projectile. The test specimens were measured for mass loss, depth of penetration and cratering post projectile firing.

An affordable and accessible construction method for creating protective concrete walls was assessed for its level of protection provided against high energy projectiles. When normal strength concrete is reinforced with 2% hook-end steel fibres, the protection against penetration is increased by a minimum of 50% and debris produced is reduced by 40% despite proper compaction. Further research and full-scale tests of this protective wall construction are required to ensure this affordable and accessible alternative can be implemented in the field.

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1 Introduction

1.1 Aim

The purpose of this research project aims to assess the suitability of normal strength concrete reinforced with short fibres in its ability to resist ballistic impacts and blasts by conducting small scale ballistics tests with comparisons to simplified empirical modelling. Protection against blast waves and high energy projectiles is becoming even more visible with armed conflicts around the world and even accidental or malfunctioned weapon systems (Beale 2024). This, combined with the ever-increasing cost and availability of resources such as ultra-high-performance concrete in which concrete blast walls are typically constructed, provides an opportunity for research to explore the effects of standard concrete blast protection walls mixed with short fibres.

1.2 Background

Infrastructure and military installations are often spatially separated to minimise the damage caused by deliberate or accidental explosive blasts (Dept. of Defence 2023). Where there is insufficient separation distance or a significant threat is unavoidable, such as in armed conflicts experienced in Ukraine or Israel, blast walls are used to protect near-by valuable and vulnerable assets from blast and projectile damage. Current blast walls employed by modern military forces can vary from multi-layered composites to ultra-high performance reinforced concrete (UHPC)(Hussein 2020, p.95). While these options achieve the highest level of protection, they come at a premium price as UHPC is approximately 20 times the cost of normal strength concrete (NSC) for approximately 5 times the strength (Ullah 2023, p. 22). While entities may have extensive budgets to afford high performance walls, there are some that might not have access to the required materials or funding.

There is a large array of literature surrounding the employment of UHP fibre reinforced concrete (FRC) under blast and projectile loading conditions with comparative tests with NSC. Through undertaking research, a gap exists in the experimenting of improved NSC (i.e. normal strength FRC), where literature is predominantly concerned with either high cost and exotic materials (UHPC, ceramic layering, polymer coatings) or very low cost in-situ materials (earth filled barriers) or plain NSC for comparisons. To help address this gap, this project will further explore the feasibility of NSC reinforced with steel fibres on its blast and projectile protection performance as a potentially more accessible and affordable material of creating blast walls.

Figure 1: A 2.75 inch rocket was inadvertently fired on ground and penetrate the earth filled blast wall (Dept. of Defence 2023).

Figure 2: Conventional RC slab under blast loading generated from 25kg of TNT (Fogar 2013).

1.3 Problems

The problems that this research project will attempt to address is the level of protection provided by concrete walls under blast and projectile loading constructed of normal strength FRC. Small scale tests will be conducted to ascertain the energy absorbed during impact and the ability to withstand blast loading. This will be done by measuring the depth of penetration, mass loss and extent of creator damage following live fire tests.

1.4 Objectives

Objective 1: Research the short fibres available.
Establish evidence that indicates the optimum choice for type and percentage of fibres in the application for blast walls.

Objective 2: Establish theoretical penetration values based on empirical models.
Generate a list of empirical formulas that cover a range of assumptions and concrete features to predict appropriate target size.

Objective 3: Construct and test specimens for high velocity projectile testing.
Produce 8 specimens for laboratory compression and tensile tests and 8 specimens for field testing.

Objective 4: Compare and evaluate results.
Compare results of control and FRC specimens, and modelled outcomes to ascertain if normal strength FRC provides improved protection performance.

1.5 Outcomes and Benefits

The expected outcomes of this project are:

1. An understanding of available options and a selection of the most appropriate fibre.
2. An understanding of the depth of target mould required in order achieve measurable results and not completely destroy the target.
3. Achieve a greater understanding of the level of protection by normal strength FRC against high velocity projectiles.
4. Reach a determination if normal strength FRC can be a viable and affordable option for blast and projectile protection walls.

The potential benefits of these outcomes include:

1. Evidence to further refine empirical penetration models to account for special reinforcement.
2. Increase investment in affordable blast wall technology.
3. More affordable protection measures for civilian and military applications for resource limited entities (highlight by the conflict in Eastern Europe).

2 Literature Review

2.1 Established Knowledge

2.1.1 Application of Blast walls

Explosive events, whether accidental or deliberate, have resulted in countless fatalities and financial costs since its conception. Blast wall systems have been developed over many years to provide blast wave and ballistic projectile protection to high value infrastructure and soft targets in both civilian and military applications. This development has led to a large array a blast wall design philosophies ranging from simple earth filled containers that can be erected in the field at minimal cost to complex multi-layered composite panels that have maximum deformation and energy absorption (Hussein 2020, p. 95). The most common design of blast wall is known as the Bremer wall or ‘t-wall’ which is a non-permanent structure and constructed of ultra-high performance reinforced concrete.

2.1.2 Blast loading

UHPC is a new material that has a wide application of uses for its enhanced flexural and tensile strength, durability, and ductility (Sherif et al. 2020, p. 2). These attributes have also seen UHPC deployed in extreme environments often experienced by blast walls regarding blast waves and high energy projectiles. UHPC gains these advantages over conventional strength concrete by ways of omission of courses aggregates, high range water reducers to achieve a water cement ratio as minimal as 0.2 and a fines only mix to increase density (Sherif et al. 2020, p. 2). Further studies have examined the behaviour of UHPC reinforced with fibres (typically synthetic or steel) at a volumetric ration of 2%, known as UHP-FRC. The fibres have shown to increase both flexural and tensile strength and fracture energy thresholds, the fracture energy being the amount of energy absorbed to create a crack of a unit area i.e., a materials ability to resist cracking. (Tran et al. 2016, p. 1). This is an important ability as under blast loading a high triaxial compressive load is introduced and subsequently converted into a tensile load once reflected off the free rear face (Zhao et al. 2019). The high energy absorption capacity of UHP fibre reinforced concrete was experimentally tested and it was revealed to be approximately 100 times greater than regular concrete in addition to a greater resistance to spalling, scabbing and overall fragmentations, which is imperative in blast wall applications as high fragmentation material can pose a hazard itself in the form of flying debris (Wahba et al. 2012). Additional engineering studies have highlighted the lower fragmentation rate is due to the presence of the fibres in the mix where they are able to bridge the gaps formed by cracks, in other words more energy was consumed in breaking the concrete mix and then pulling out the embedded fibres in the cracked sections (Mao et al. 2015, p. 829). This is in addition to producing a material with a more ductile failure mode, when compared to both high-strength and normal strength non-fibre reinforced concrete of same geometry (Yu 2015, p. 242).

Due to high cost of materials needed, UHP-FRC has seen limited use in applications other than skyscrapers and offshore structures, however it is anticipated that market interest will expand high performance protective shields for structures (Sherif et al. 2020, p. 3).

2.1.3 Projectile loading

Ballistic protection is another critical function of blast wall systems, as explosive detonations can create large quantities of flying debris know as fragmentation and high velocity projectiles intentionally fired out of weapon systems are common to conflict regions.

When a concrete surface experiences a high velocity impact load, such as from a projectile or fragmentation, this will generate a compressive stress wave through the material until it reaches the rear face in which it reverts to a tensile stress wave. This motion is what will generally cause local failure in the following forms (Clifton 1982, p.5).

a. Cracking – hairline fracture on the impact and/or rear face
b. Scabbing – fragments ejected from the rear face
c. Spalling – fragments ejected from the impact face
d. Cone cracking – radial cracks from a cone/plug that results in shear failure
e. Penetration – tunnelling into the target but not passing though
f. Perforation – passing though the material.

To increase a materials resistance to these forces induced by high energy impacts, reinforcement can be introduced to increase the concretes tensile strength. Studies have been conducted on the effects of ratio and types of reinforcement and how these parameters increase or decrease a materials ability to resist damage. Chen et al. (2008) is an example of this, in which they investigated the depth and layout of reinforcement bars and the relationship of crater shape and depth, and made comparisons to existing experimental data and empirical formulas for calculation penetration predictions. Their results indicated that the characteristic strength of the concrete plays a larger function in preventing perforation than the amount of reinforcement. While reinforcing bars did marginally increase the ballistic limit of the samples (velocity required to consistently perforate a material), the major improvement was the reduction of cratering and fragmentation on the rear face.

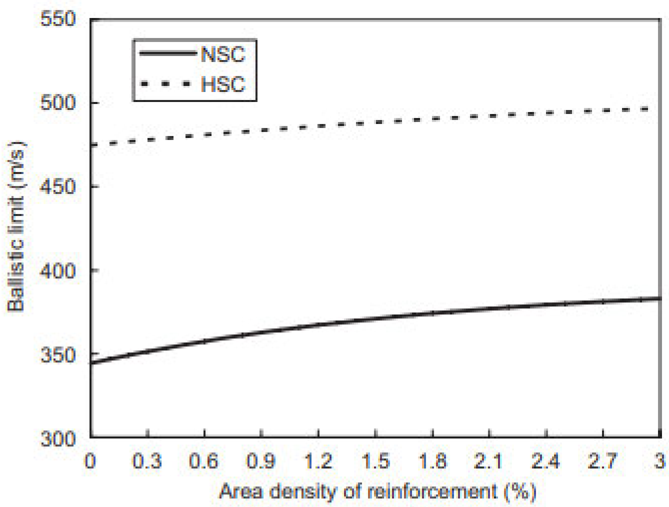

Figure 3: Variation of ballistic limit with the reinforcement ratio (Chen et al. 2008)

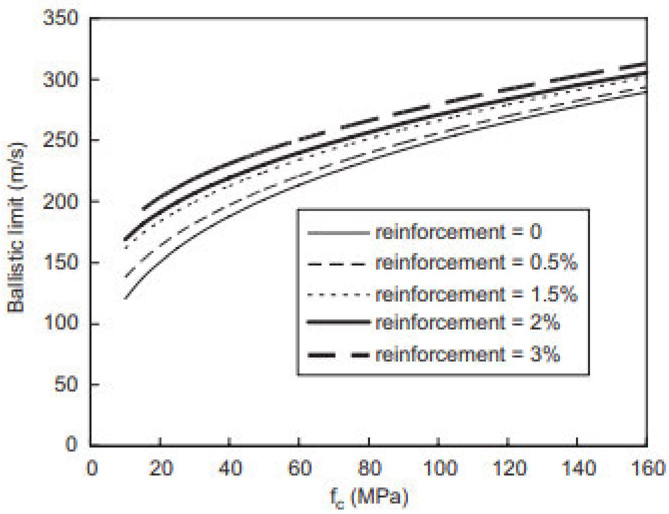

Figure 4: Ballistic Limit vs characteristic strength for differing reinforcement ratios (Chen et al. 2008)

To improve the material's energy absorption and impact resistance capacity, the mix must be prevented from being separated from itself and the embedded reinforcement (Tran et al. 2016, p. 149). The most common application of this is the introduction of steel reinforcement bars which has seen wide use in civil context. Whilst this method increases the tensile strength of the concrete mass, it has been established to be ineffective in reducing the depth of penetration and cratering under high energy projectile impacts (Luo et al. 2000, p. 908).

Another variable that has been studied regarding projectile protection has been the effect of aggregate size and strength properties on the material at impact face. It was observed while firing a 7.62 mm (NATO ammunition) bullet shaped projectile that stronger aggregates were able to absorb more kinetic energy at impact and further altered the projectile path after penetrating, furthermore the specimens constructed with more ductile aggregates exhibited better performance (Tran et al. 2016, p. 148). Despite such conclusive research, there are still conflicting studies regarding the philosophy of the optimisation of aggregate in concrete mix for projectile protection. There is still ongoing research whether a homogenous concrete mix or large aggregates are the most influencing factors in impact resistance concrete design (Tran et al. 2016, p. 149).

Máca et al. 2014 conducted similar tests with UHPFRC, UHPC, FRC and normal strength concrete (NSC) by creating 300mm x 400mm x 50 mm slabs and firing a 7.92mm (non-NATO ammunition) armour piercing projectile at a range of 20 m. The study primarily focused on the difference between UHPFRC and UHPC in terms of penetration, mass loss and cratering on both sides. The results indicated that a 2% volume of fibres achieved the greatest level of protection (50% reduction compared UHPC) while anything greater than 2% had negligible improvement on crater size and decreased the specimen compressive strength (Máca et al. 2014, p. 163). Limited testing was done on the FRC and NSC samples and the energy provided by the projectile, 7.92mm being on the larger side of small arms ammunition, resulted in 100% penetration of the samples and the loss of measurable data on the comparison of FRC to NSC protection abilities. As these 2 materials were not the focus of the study, the same methodology can be applied to a similar test with a lower energy projectile to measure the performance of FRC and NSC without over penetrating the samples, resulting in inconclusive data.

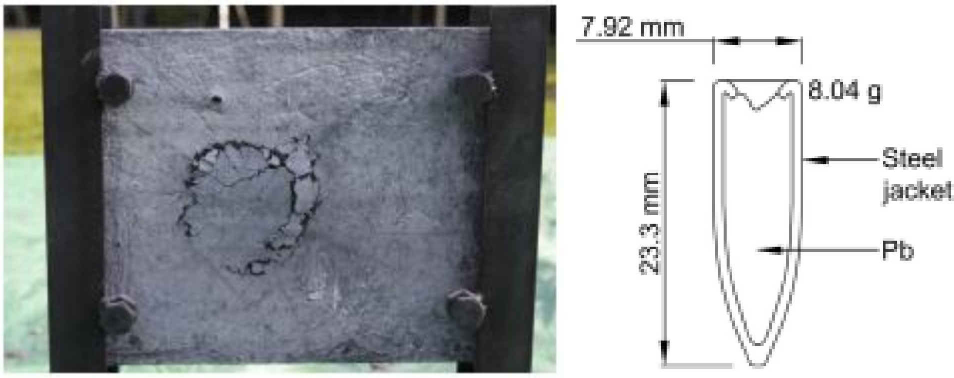

Figure 5: Borders of the crater on the back side of the 50 mm thin UHPFRC slab after 7.92mm projectile impact (fragment is still attached to the slab) (Máca et al. 2014, p. 162).

2.1.4 Empirical Models for Concrete Penetration

Many empirical formulas for calculating concrete penetration depth have been developed during the early to mid-20th century when computational power was still in its infancy, in which they relied on large arrays of experimental results to determine a response database. Existing models will generally incorporate parameters from the projectile, being velocity, shape, mass and diameter and the concrete targets compressive and tensile strength. Though, there are still variations in how certain penetration characteristics affect the target. For example, the US Army Corps of Engineers (ACE) (Chelapati et al. 1972, p.362) and modified Petry model (Chelapati et al. 1972, p.362) do not account for the shape of the projectile's nose while models such as the Modified National Defense Research Committee (NDRC) model does (Che Muda et al. 2013), despite being limited to basic shapes (flat, blunt spherical and sharp). Furthermore, the models identified in this literature review do not factor in aggregate size, except for the Whiffen model (Bookout 2011, p.4), despite later studies mentioned in this literature review establishing how aggregate sizes can affect ballistic and compression performance. This highlights an area of further research regarding concrete penetration prediction.

Table 1: Concrete Penetration Models

Year	Model Name	Formula	Projectile shape factor (N)	Applicable range	Ref
1946	Us Army Corps of Engineers (ACE)	$\frac{x}{d} = \frac{3.5 \times 10^{-4}}{\sqrt{f_c}} \left(\frac{M}{d^3}\right) d^{0.215} V^{1.5} + 0.5$	n/a	n/a	Chelapati et al. 1972
1910	Modified Petry	$\frac{x}{d} = K\left(\frac{M}{d^3}\right) log10\left(1 + \frac{V^2}{19,974}\right)$ K=6.36x10^{-4} for plain concrete, 3.39x10^{-4} for normal reinforced concrete, 2.26x10^{-4} for specially reinforced concrete	n/a	n/a	Chelapati et al. 1972
1946	Modified National Defence Research Committee (NDRC)	$G = 3.8 \times 10^{-5} \frac{N \times M}{d\sqrt{f_c}} \left(\frac{V}{d}\right)^{1.8}$	0.72 (blunt) 0.84 (blunt) 1 (spherical) 1.14 (sharp)	n/a	Che Muda et al. 2013
1943	Whiffen	$\frac{x}{d} = \frac{2.61}{\sqrt{f_c}} \left(\frac{M}{d^3}\right) \left(\frac{d}{a}\right)^{0.1} \left(\frac{V}{533.4}\right)^{n}$	n/a	$5.52 < f_c < 68.95$ $0.136 < M < 9979.2$ $12.7 < d < 965.2$ $0 < V < 1127.8$	Bookout 2011

Where x is the penetration depth (m), d is diameter of the projectile (m), f_c is the concrete compressive strength (N/m^2), M is the projectile mass (Kg), V is the projectile velocity, K is the coefficient for concrete penetration, G is the impact function, N is the projectile nose shape factor, a is the maximum size of aggregate.

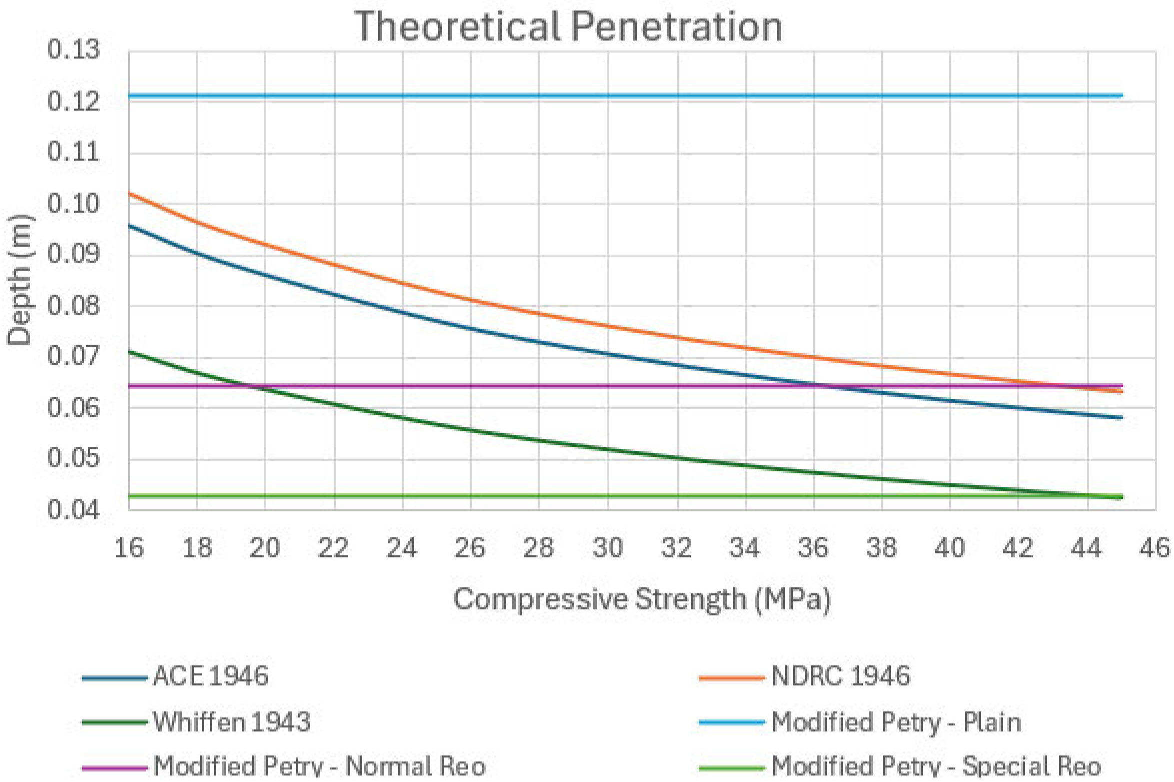

Figure 6: Theoretical penetration depths for various compressive strengths based on a 5.56mm projectile at 920 m/s

2.1.5 Types of Fibres

Studies have shown that incorporating fibres into concrete can enhance structure properties and issues associated the curing process such as shrinkage and creep deformation (Khan et al. 2022, p. 5). There is a wide variety of fibres available to be used in concrete such as steel, glass, polypropylene, carbon, and natural fibres.

Steel fibres are the most utilised material for FRC given its availability and mechanical performance regarding improvements in compressive and tensile strength, toughness, cracking resistance, and a ductile mode of failure which is often more predictable (Khan et al. 2022, p. 2). The drawbacks of steel fibres are predominantly around the soft properties of the mix such as decreased workability and the need for superplasticisers to ensure an even distribution and orientation of the fibres. The nominal range for steel fibre volume is 0.5% - 2%, as studies have shown this to result in the most effective performance particularly in impact loading and energy absorption (Khan et al. 2022, p. 2).

Glass fibres can be used in place of steel fibres where the concrete may be exposed to corrosive environments such as marine, freeze-thaw and high UV environments where the steel reinforcement and cover can be corroded over time (Vamsi Krishna 2015, p. 5). Many of the benefits are shared with steel fibres, with the omission of improvement in compressive strength, but with the improvement of maintaining strength when experiencing higher temperatures (Khan et al. 2022, p. 3). A non-structural benefit of glass fibres is the recycling of industrial waste.

The use of plastic fibres in concrete differs from glass and steel fibres, as it has been researched not necessarily as a major improvement to concrete properties but as a method of utilising waste products being plastic (Khan et al. 2022, p. 4). Plastic fibres reduce the cost of construction as part of the reinforcement is a low cost 'eco-friendly' recycled material with the additional benefits of increase tensile strength, flexural behaviour and can induce a ductile mode of failure (Baldenebro-López et al. 2014, p. 16). The resistivity to chemical and bacterial attacks however come at a cost of reduced compressive strength and may require additives (Baldenebro-López et al. 2014, p. 16). It also increases the chance of spalling, which is detrimental for blast walls as this can create more fragmentation during blast events.

Carbon fibres have seen limited industry use due to their high costs despite being a lighter and higher strength material when compared to metallic and synthetic fibres. The presence of carbon fibres enhanced the flexural capacity by almost double but have little influence on compressive strength at a volume of 0.75%. A limiting function of the fibre volume was the decrease in workability, compaction and longer mixing times (Aljalawi & Al-Jelawy 2018, p. 1).

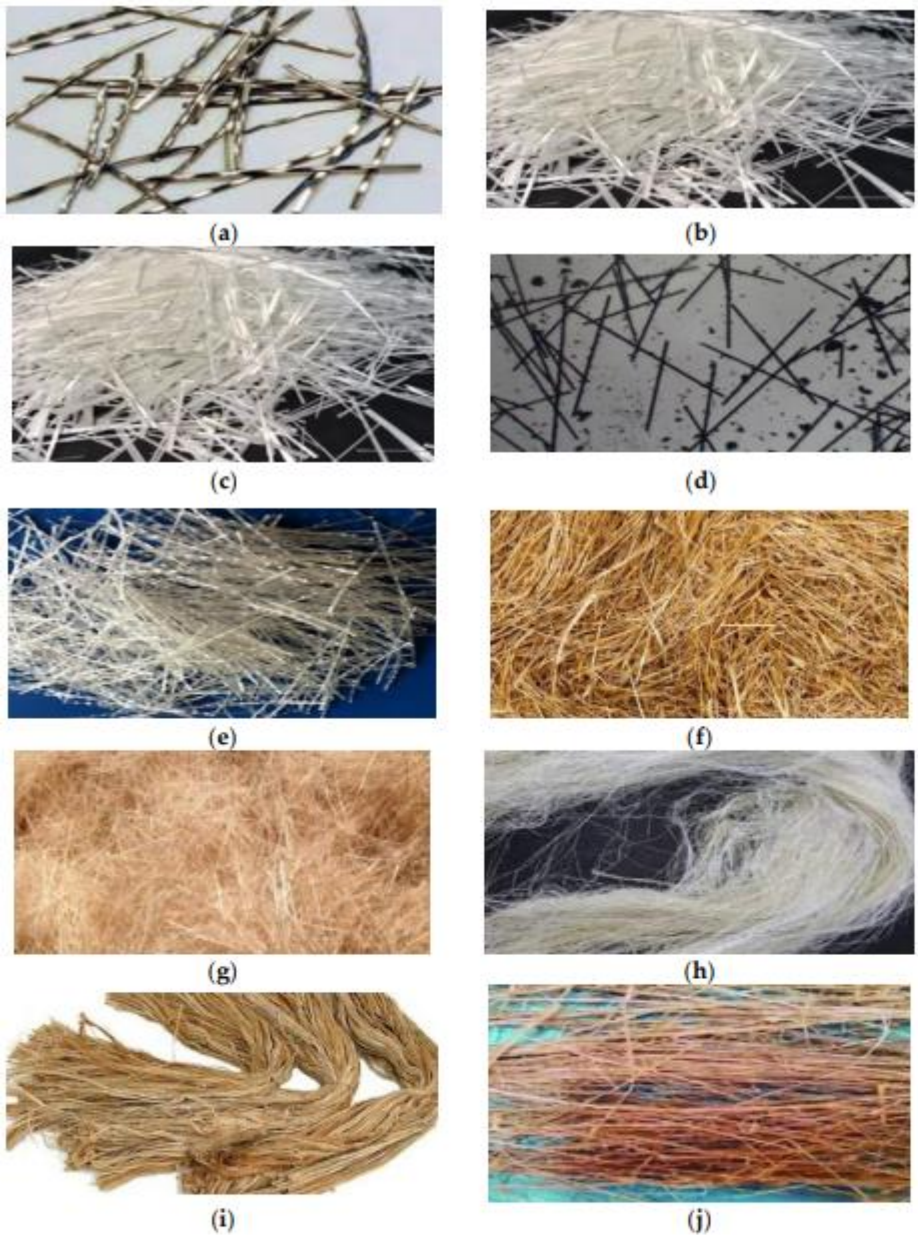

Figure 7: (a) Steel, (b) Glass, (c) Polypropylene, (d) Carbon, (e) Plastic, (f) wheat straw, (g) Sugarcane, (h) Sisal, (i) Jute, (j) Bamboo (Khan et al. 2022, p. 2)

Table 2: Fibre Tensile strength (Cement Concrete and Aggregates Australia. 2024, Khan et al. 2022)

Fibre Type	Tensile Strength (MPa)
Steel	800
Glass	1400
Polypropylene	300
Carbon	600
Plastic	38
Wheat Straw	21
Sisal	385
Jute	300
Bamboo	150

2.2 Knowledge Gap

2.2.1 Study Justification

Whilst there is an extensive body of knowledge surrounding UHP-FRC and its performance regarding blast and projectile protection, there has been an oversight on the feasibility of normal strength FRC and its comparison with normal strength steel bar reinforced concrete. The proposed experiment in the following chapter will enable an investigation and provide real life data on the extent to which normal strength FRC can provide protection to medium behind the rear face without the high cost and resource intensive UHP-FRC or complex mixtures.

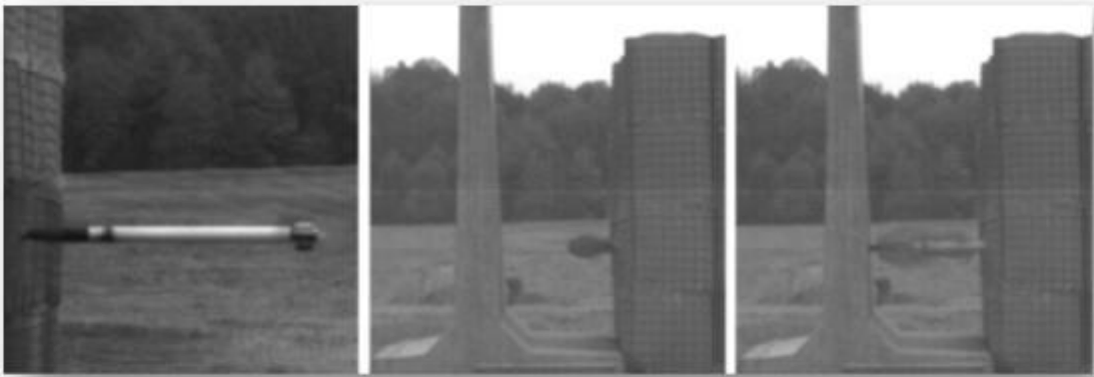

Figure 8: A demonstration of a rocket penetrating a normal strength steel bar reinforcement blast wall and earth filled wall. (Dept. of Defence 2023)

If deemed feasible, it can provide a cost-effective method of construction from blast wall systems for financial and resource restricted groups.

2.2.2 Project feasibility

The literature research conducted has highlighted that ballistic and blast test can be conducted in relatively simplistic manners whilst still achieving conclusive outcomes. The time restriction of 2 t is a suitable period which can be illustrated by the timeline below, with sufficient led and lag time for each milestone (with the caveat of Defence Science and Technology group (DSTG) availability). The specimen material and casting can be gathered from local suppliers and access to hydraulic press' can potentially be sought from DSTG, ADFA and local concrete suppliers if required. The small scall of the experiment reduces the risk and exposure to explosive and other hazardous materials.

3 Methodology

3.1 Project Parameters

3.1.1 Scope

The scope for this project was separated into 3 stages.

1. Empirical Model analysis
2. Creating laboratory and live fire test specimens
3. Testing laboratory specimen properties and live fire of the field specimens

It was essential to have an awareness of the specimen (control and FRC) properties before conducting any experiments. However, empirical models were used based of theoretical values gathered from literature and were subsequently modified when destructive testing (unconfined compression and Brazilian tensile strength) returned significantly lower results. The primary purpose of the modelling was to ensure the specimens can withstand the energy introduced by the projectile and were not completely destroyed, thus returning little quantifiable data for analysis. Live fire ballistics tests were conducted with comparisons of both control and FRC specimens to empirical calculations and recorded results. Conclusions were made on the suitability and performance for the FRC samples which fulfill the projects primary parameter.

3.2 Project Experiments

3.2.1 Dry Mix Particle Distribution

A dry mix particle distribution test was conducted to determine the proportion of cement, sand and aggregate of the premixed dry concrete. The sieve analysis was done with the use of a mechanical shaker to save time, as multiple sieve sizes can be done simultaneously and produce a more consistent sieving action. The test mix portion and procedure were conducted IAW AS1141.11.1:2020 – Methods for sampling and testing aggregates. The manufacturer product data sheet indicated that the mix contained 7-10mm aggregate so 800g was measured for the test and the sieve sizes ranged from 0.075mm – 9.5mm.

Table 3: Minimum Mass for Sieve Testing

Nominal size mm	75	40	28	20	14	10	7	5	Fine aggregate	Fillers
Graded aggregate	30 kg	15 kg	5 kg	3 kg	1.5 kg	800 g	500 g	300 g	150 g	25 g
One-sized aggregate	25 kg	10 kg	4 kg	1.5 kg	700 g	500 g	300 g	200 g	100 g	-

Figure 9: Sieve Shaker

3.2.2 Creating Laboratory Control and FRC Test Specimens

The specimens were initially cast in 2 batches, being the control mix without steel fibres and the 2% steel fibre reinforced mix. The 2% didn't achieve proper compaction in the 50 or 210 mm moulds and the material property specimens were abandoned as they would have failed the requirements for UTS testing, however the targets we kept. The FRC portioning was changed to 0.5% and 1% to ensure compaction was achieved without further delays, as compaction observations cannot occur until specimens are removed from the mould.

Figure 10: Failed 2% compressive test sample

The mix constituents were attained from local hardware stores, and the ratios to be followed were as per manufacture guidelines to achieve a target strength of 40 MPa 28-day strength. The specimens were removed from the moulds and covered in wet fabric to cure. 8 control and FRC targets were created to allow for 4 projectile tests of each mix. The targets were cast in 21x7 cm circular moulds to ensure consistent shape and impact surface texture, and compacted with a vibrating device as the steel fibres greatly reduced workability. Admixtures to increase workability were not included as this was outside of the intention of the project being the testing of DIY protective blast walls with commonly available material, simulating a resource limited environment. The specimens for mechanical property tests were cast in 50mm diameter PVC piping and cut to the required length for compression and indirect tensile tests in accordance with AS1012 – Methods of Testing Concrete. The moulds were glued to plastic boards to ensure a smooth bottom surface/edge and no leakage of fines or water. The PVC pipe moulds were cut vertically to remove the sample for curing.

Figure 11: Mechanical Property moulds for Laborartory Specimens

Figure 12: Target molds 2% FRC (L), Control (R)

3.2.3 Specimen Tensile and Compressive Strength Properties

Cylindrical PVC moulds were chosen as a cost effective method of achieving the appropriate size of specimen required for the compressive and tensile strength tests whilst using minimal materials. Compressive strength was determined by preforming an unconfined compression strength test in accordance with AS1012.9:2014, and tensile strength determined by preforming a Brazilian / splitting test in accordance with AS1012.10:2014. Access to the hydraulic press was sought from UNSW at ADFA. The hydraulic press recorded force, time and deflection.

These tests allow the calculation of specimen material characteristics for use in the empirical formulas mentioned previously to predict penetration depth and allow comparison with experimental data.

Figure 13: Hydraulic press (L), UCS (M), Brazil (R)

3.2.4 Live Fire on Field Specimens

Testing specimen projectile protection performance took place at a remote private property outside of Canberra. Projectile tests were carried out by remotely firing a .223 calibre rifle (5.56mm projectile) via string mechanism at a range of 20m from behind the protection of sandbags and timber.

Figure 14: Firing position

Firing tests were conducted on 4x control and 4x FRC samples to observe any differences in depth of penetration, volume/mass loss and crater size. The target was surround by sandbags to capture large fragments and any projectile deflections if minimal penetration occurred. Targets were simply supported with vertical timber supports at each end and 60kg mass was placed at the rear to prevent any rearwards movement during impact. Post event visual inspection for impact crater, projectile (if imbedded in target or captured in the rear support), penetration depth, exit crater and volume/mass loss measurements were observed. Cratering also offered to opportunity to examine the compaction of the concrete mix and the fibre distribution and orientation with further comparison to the material property test specimens.

Figure 15: Test setup for Control and FRC

3.3 Project Planning

3.3.1 Resources

Table 4: Equipment and resources required.

Item	Quantity	Source	Cost ($)	Comment
Premixed cement	3	Student	45	Total 60kg of concrete
water	7.2kg	Student	N/A	
Steel Fibres	1kg	Student	$30	
Mixer/wheelbarrow	1	Student	N/A	
Shovel/spade	1	Student	N/A	
Target molds	8	Student	40	
Compression/tensile test molds (PVC pipe)	8	Student	40	
Compression/tensile test equipment	1	UNSW at ADFA	N/A	
Vehicle	1	Student	N/A	
Test range	1	Student / Defence	N/A	
Rifle	1	Student / Defence	N/A	
Ammunition	10	Student / Defence	TBC	
Explosives	1 kg TNT (e)	Defence	TBC	
Stand7 software subscription	3 months	Student	30	Student (needed for CIV4508)
High speed camera	1	Defence	N/A	
Specimen test stand	1	Student	30	
Scales	1	Student	N/A	
Saw	1	Student	N/A	
Concrete vibrator	1	Student	$60	
Sieve vibrator	1	UNSW at ADFA	N/A	

3.3.2 Project schedule

Task	Semester 1B						recess		Semester 1B									Recess			Semester 2A										Recess		Semester 2B			Task
Task 1 - Project Prepareation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Task 1
A - Commencement Approval																																				A
B - Resource Acquisition																																				B
C - Drafting																																				C
Task 2 - FE model (STRAND 7)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Task 2
A - CIV4508 II																																				A
B - Create Simulation Model																																				B
Task 3 - Samples	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Task 3
A - Cast control samples																																				A
B - Cast FRC samples																																				B
C - Test Sample Properties																																				C
Task 4 - Live Fire	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Task 4
A - Travel to DSTG (Edinbourgh)									E											T							L									A
B - Data Acquisition									E											T							L									B
C - Data Analysis									E											T							L									C
Task 5 - Project Finalisation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1	2	3	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Task 5
A - Project Presentation																																				A
B - Paper Completion																																				B

Note: Task 4 A & B dates are subject to DSTG availability

E = early as feasable

L = late as feasable

T = Target date

4 Results and Discussion

4.1 Material Properties

The strength of concrete plays a significant role in the level of protection provided against high energy projectiles and preventing debris. Test results for the hardened specimen tests conducted were compressive strength test, Brazilian tensile strength and the effects of steel fibre reinforced normal strength concrete were also assessed.

4.1.1 Compressive Strength Test

The table below illustrates the outcomes of the compression tests conducted on the control and 1% fibre specimens. It can be seen that the fibre reinforcement has increased the compressive strength by 3.5 MPA which translates to 20 %. It was observed that the fibre specimens had noticeably less compaction due to the increase in air bubbles and exposed aggregate. They also typically failed along vertically orientated fibres as they would buckle from near the surface of the specimen. The results were significantly lower than the target strength of 40 MPa. This was suspected to be due to the delay in curing, as the specimens were removed from the moulds and wrapped in wet fabric 5 days after casting. Compressive strength is an important factor in high velocity impact loading as the compressive stress generated from the projectile will often cause material to be ejected from the rear face, known as scabbing, in addition to increasing the ballistic limit of the material. It also directly affects the crater produced on the impact face as the concrete is crushed under the compressive load of the projectile.

Table 5: Compressive Strength Results

Sample	W (kg)	H (mm)	D avg (mm)	Density (kg/m³)	Load (kN)	Compressive (Mpa)
Control	0.484	100	50	2466	32267	16.433
1% FRC	0.488	100	50	2485	38983	19.854

4.1.2 Brazilian Tensile Strength Test

The table below shows the outcomes for the Brazil tensile strength test conducted on the control and 1% steel fibre reinforced specimens. The increase in strength is due to the fibers carrying a portion of the load until the bind between concrete and fibre fails and is pulled out from the concrete mix. It can be seen that a significant amount of force was required to de-bond the fibre from the concrete matrix prior to failure of the specimen. This is a valuable property to have for the protection against high velocity impact loading, as the projectile not only burrows into the concrete matrix, but also ejects material in the form of spall (front side) as the local area experiences the reflective tensile stress wave post impact. The sample did not split sufficiently to examine the fibre distribution within the specimen, acknowledging that the 35mm fibre could only be horizontally positioned in the 25mm high by 50mm diameter specimens.

Table 6: Tensile Strength Results

Sample	L (m)	D (m)	P (kN)	Tensile (Mpa)
Control	0.025	0.05	4.86	2.475
1% FRC	0.025	0.05	8.84	4.502

4.2 Sieve Analysis

The figure below illustrates the particle distribution as a result from the sieve analysis of the dry concrete mix. The 800g sample revealed that the mix was mostly well graded with a gap grade between 2.36mm and 0.6mm with only 8% of the sample retained on the 3 sieves. This type of grading is typically used in high strength concrete as the smaller sized aggregate can fill gaps between larger sizes when compared to a well graded mix where particle seizes are evenly distributed. The fines portion of the mix was repeatedly cycled through as the cement powder would stick to the edges of the sieve or form small chucks on the seal of the sieve, this was repeated until there was no cement coloration in the fine (0.15-0.075mm) portions.

The small percentage of larger aggregate, being of 9mm of greater, will increase the penetration resistance of the target only if the projectile's path aligns with the larger aggregate. While the focus of this research project is not on the effects of aggregate parameters of projectile loading, this aspect will have an influence on the experiment results.

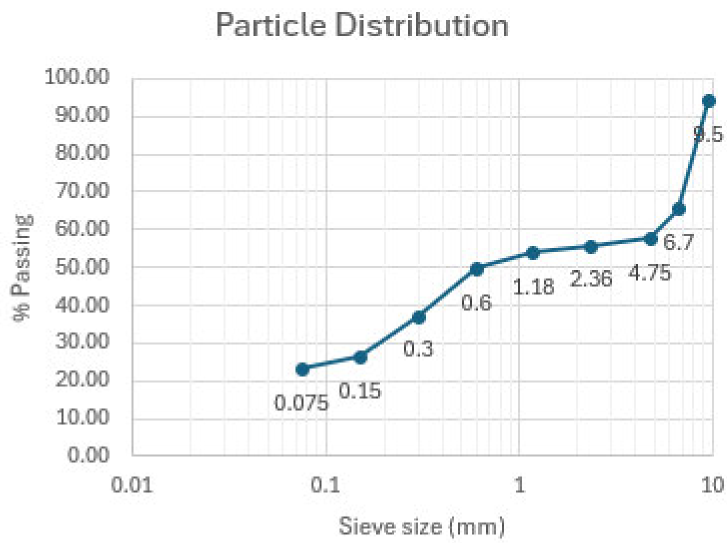

Figure 16: Sieve analysis for dry concrete mix

4.3 Ballistic Properties

Table 7: Ballistic Results

			Spall (Front)		Scab (Rear)		
Sample	W (kg)	Density (kg/m^3)	depth (mm)	width (mm)	depth (mm)	width (mm)	W loss (kg)
Control	4.318	2291	P	170*	P	150*	4.318
1% FRC	4.286	2274	P	90	P	80	0.296
2% FRC	4.429	2425	35	55.5	0	0	0.180

4.3.1 Control

The control samples experienced complete perforation with spall and scabbing ejected from the majority of both faces to a distance of 150mm. Radial cracking extending to the outer edges and propagated thickness of the target which resulted in the target being separated into smaller pieces. Whilst the control samples yielded less quantifiable measurements such as crater size and mass loss, the lack of available equipment such as ballistic chronographs or highspeed cameras also impeded data gathering opportunities (residual velocity, impact time and target behaviour) for such an outcome, however the concrete mix was able to be examined for compaction and aggregate distribution in addition to providing a baseline for the FRC samples. Good compaction was observed throughout the target with occasional voids on the outer edges. After material property testing revealed the drastically lower strength of the specimens (40% of the target strength, 40MPa), empirical models predicted that the ballistics test would cause severe damage to the targets, via complete penetration, and data collection would be limited without the use of high-speed cameras or ballistic chronographs. This large reduction in compressive strength can be observed in the impact face crater width of approximately 170mm where the concrete mix is crushed under the impact load, separating the cement and aggregates. The recorded results also aligned with modified Petry – plain, NRDC and ACE formulas which required a depth of 9mm or more to prevent perforation (field targets were 7mm) while Modified Petry predicts 12mm is required to theoretically prevent complete penetration.

Figure 17: Control target CD

4.3.2 1% FRC

The 1% FRC targets experienced perforation but with less damage compared to the control targets. Average spall diameter was reduced by 60mm and scabbing by 70mm, with radial cracking extending part way to the target edges. Where mass was ejected, it can be observed that the hook-end steel fibres have been straightened or elongated as the concrete mix has lost bonding and the steel pulled out from the ejected material. The 5.56mm projectile generated a rear crater of 20mm depth which indicated a punching-shear plug scenario between the projectile nose and rear face of the target. This increase in compressive strength from 16 MPA to 20 MPa can also be observed by the smaller impact face crater of approximately 80 mm as less material was crushed and turned into debris, a reduction of 53% when compared the control targets. Radial cracks were also minimised as the steel fibres would carry a portion of the tensile loading post impact. An average of 0.296kg of mass was loss, which is a significant improvement compared to the controls of 100%. The 1% FRC targets also returned a lower average density (71 kg/m³ less) compared to the control which indicated a reduction in compaction as steel has a higher density of 7850 kg/m³ compared to concrete of 2300 kg/m³. The fibre distribution was dispersed throughout the targets; however, it was observed that all visible fibres in the centre were orientated horizontally toward the centre of impact instead outwards in the direction of ejected mass. This could be due to the last position of the vibrating device during casting or elastic deformation behaviour of the steel fibres as they were ripped out of the concrete mix.

At the compressive strength of 20 MPa, ACE and NRDC formulas predicted that 8.5-9.5mm of material would be needed to prevent penetration, while Modified Petry normal reinforcement and Whiffen under predicted at 6.5mm (target thickness was 7mm). Assessing the damaged caused projectile and resulting shear-plug, ACE and NRDC are closer to experiment results as they indicate a significant amount of material needs to be added to prevent penetration.

Figure 18: 1% FRC target 1C, Front (L), Back (R)

4.3.3 2% FRC

The 2% targets experienced a penetration depth of 35mm with even less damaged observed compared to the 1% targets. Average spall width was 56mm with no scabbing damage to the rear face and small radial cracks that extended 50mm from point of impact. The lack of shear-plug failure in the rear face resulted in a stronger reflective tensile stress wave towards the front face, this can be observed by small fragments on the extremities of the impact zone that have been lifted but remained attached via embedded fibres. The fibres on the impact face were also oriented outwards against the direction of the projectile, this is again evidence of the reflected tensile stress wave being transmitted to the front face. Mass loss was 0.18kg which is 0.11kg less than the 1% targets, an improvement of 40%. The targets had very poor compaction as large voids could be seen on target extremities and worked surface. Despite this, they still had a density of 2425kg/ m^3 which was 143kg/m^3 higher than control and 151 kg/m^3 greater than 1% targets. The dense concentration of fibre in the centre of the target appears to have created a mesh condition where the impact load (compressive and tensile) is distributed across fibres anchored into the concrete mix but also against other fibres. This was not observed in the 1% targets as many of the fibres were generally separated by concrete mix. The projectiles were unable to be recovered, with one being lodged within the impact zone.

The only formula which accurately predicted the penetration of the 2% targets was Modified Petry – special reinforcement. For this project, hook-end steel fibre reinforcement was considered as special reinforcement as it is not the standard reinforcement used in either the general civilian infrastructure or military installations. It closely predicted the penetration value to within 5mm, however this value is independent of the concrete’s compressive strength.

Figure 19: 2% FRC target 2A, front (L), side (M), back (R)

5 Conclusion

5.1 Project Achievement

The primary objectives of this research project have been satisfied and are briefed below.

1) Research was conducted on types of fibers that can be used to increase various properties of concrete for the purpose of protecting against blast and projectile loading. It was found that the optimum ration of 2% volume of steel fibers offers the highest level of strength increase for normal strength concrete.

2) Various empirical models were identified during the literature review and 4 were chosen based on different assumptions and aspects of concrete and reinforcement. It was found that models were created post major conflicts such as the world wars before modern computation and then modified as trials and computational abilities increased to cover a range of ballistic interactions.

3) A number of 0%, 1% and 2% FRC specimens were cast to facilitate material property testing and high velocity impact testing. It was found that 2% FRC mix needed larger moulds to account for the reduction in workability and the exclusion of additives, however 1% FRC mix can be adequately compacted with common concreting equipment

4) Results from the live fire test and modelled outcomes for control and FRC specimens were assessed and compared. It was discovered that increasing the percentage of fibre by volume to 2% had a significant reduction in debris produced and penetration depth caused by high velocity projectiles despite improper compaction of the concrete mix and that models that accounted for special reinforcement, such as hook-end steel fibers, predict penetration values to within 5mm. Blast testing was unable to be conducted due to loss of assistance.

5.2 Conclusion

Many literature reviews have identified that fibre incorporation into concrete can play a significant factor in improving the mechanical properties. The majority of research into ballistic performance of concrete and the incorporation of steel fibres is orientated around ultra-high performance concrete, as high velocity projectile and blast loading creates an extreme environment in which maximum performance is necessary for maximum protection despite the high cost.

The casting and testing of steel FRC indicated that 2% fiber incorporation greatly reduces the workability of the wet mix to the point where it cannot be compacted into small 50mm diameter moulds without additives, while 1% can easily be done with common materials and tools. The fibres greatly improved the concretes ability to resist high velocity impact load by a minimum of 50% in terms of penetration and 60% for fragmentation generated. The ability of fibers to carry a portion of the load is significantly greater than the reduction in concrete strength from air voids due to improper compaction. With UHPC at approximately 20 times the cost for a 5 times increase in strength, normal strength FRC can provide 2 times the protection for a cost increase of 15% resulting in a cost effective solution for protection against high energy projectiles.

There are many examples of conflicts around the world in resource limited situations where assets or infrastructure require protection against projectile and blast loading. The demand for cost effective and accessible solutions allows for further research of this concept, being blast/protective walls made from commonly accessible and affordable materials. This is a real world solution that could see implementation in conflict zones or areas of civil unrest to provide a greater level of protection than standard construction methodologies or existing expensive solutions. Blast testing and further analysis is required to determine the level of protection provided against blast loading to account for other threat stimuli.

5.3 Recommendations for further study

Continued research is necessary for this project to translate into the full scale application. This would involve full scale walls functionally tested against large caliber weapon systems and explosive events.

These live fire tests could be made more useful by using the experimental results to validate CFD programs.

Recreating this experiment with properly cured concrete to the original target strength of 40 MPA will allow for more data gathering opportunities and comparisons from control to FRC specimens in terms of projectile penetration and fragmentation. Additional equipment to gather data such as highspeed cameras for behaviour at impact, ballistic chronographs for more accurate impact and exit velocities and a soft capture device to retain projectile post impact could be utilised.

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APPENDIX A - Project Specification

For: Aaron Marshall

Title: Feasibility of Blast Walls Constructed with Normal Strength Fibre-Reinforced Concrete

Major: Civil Engineering

Supervisor: Dr Habib Alehossein

Enrolment: ENP4111

Project Aim: The purpose of this research project aims to assess the suitability of normal strength concrete reinforced with short fibres in its ability to resist ballistic impacts and blasts by conducting small scale ballistics tests and simplified dynamic modelling.

Objective 1: Research the short fibres available.
Establish evidence that indicates the optimum choice for type and percentage of fibres in the application for blast walls.

Objective 2: Model potential samples.
Create a finite element model to simulate impact and blast pressure on test specimen theoretical properties to initially check if loads can be absorbed.

Objective 3: Construct and test specimens for projectile and blast testing.
Produce 8 control specimens and 8 test specimens and test for material properties and test criteria.

Objective 4: Compare and evaluate results.
Compare results of control, test, and modelled outcomes to ascertain if normal strength FRC provides improved protection performance.

APPENDIX B - Test Results

Table B1: Sieve Analysis

Sieve Size (mm)	Mass of Sieve (g)	Mass of sieve & retained (g)	Mass of retained (g)	Mass Passing	% Passing
9.5	469.5	517.8	48.3	751.7	93.96
6.7	464.8	694.5	229.7	522	65.25
4.75	445.6	506.9	61.3	460.7	57.59
2.36	404.5	420.5	16	444.7	55.59
1.18	362	374.9	12.9	431.8	53.98
0.6	323.5	358.5	35	396.8	49.60
0.3	293.9	394.1	100.2	296.6	37.08
0.15	260.7	346.5	85.8	210.8	26.35
0.075	264.8	290.5	25.7	185.1	23.14
Pan	240.8	425.9	185.1	0	0
Total			800		

Table B2: Tensile test

Sample	L (m)	D (m)	P (kN)	Tensile (Mpa)	Avg
CA	0.025	0.05	-	-	
CB	0.025	0.05	5.32	2.709	
CC	0.025	0.05	4.29	2.185	
CD	0.025	0.05	4.97	2.531	2.475
1A	0.025	0.05	-	-	
1B	0.025	0.05	8.34	4.248	
1C	0.025	0.05	9.82	5.001	
1D	0.025	0.05	8.36	4.258	4.502

Table B3: Compression test

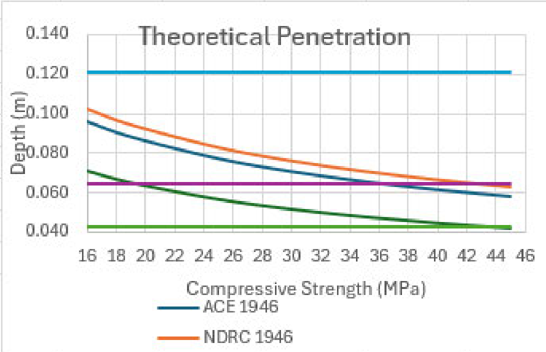
Sample	W (kg)	H (mm)	D avg (mm)	Density (kg/m³)	Load (kN)	Compressive (Mpa)	Avg
CA	0.49	100	50	2496	29880	15.218	
CB	0.478	100	50	2434	28820	14.678	
CC	0.484	100	50	2465	38100	19.404	16.43
CD	0.485	100	50	2470	-		
1A	0.491	100	50	2501	-		
1B	0.494	101	50	2516	-		
1C	0.484	100	50	2465	39045	19.885	
1D	0.483	100	50	2460	38920	19.822	19.85

Table B4: Ballistic test

			Spall (Front)		Scab (Rear)			
Sample	W (kg)	Avg (kg/m^3)	depth (mm)	width (mm)	depth (mm)	width (mm)	W new	W loss
CA	4.464	2291	P		P			
CB	4.34		P		P			
CC	4.279		P	200	P	200	0	4.279
CD	4.19		P	200	P	200	0	4.19
0.5A	4.005	2173						
0.5B	3.989							
0.5C	4.128		P	120	P	100	3.66	0.468
0.5D	4.259							
1A	4.167	2274						
1B	4.384							
1C	4.362		P	85	P	70	4.046	0.316
1D	4.23		P	95	P	90	3.955	0.275
2A	4.738	2425	36	62	0	0	4.654	0.084
2B	4.405		35	49	0	0	4.332	0.073

Table B5: Penetration calculations

concrete compressive strength (MPa)	fc	16	19	25	30	35	40	45
diameter of the projectile (m)	d	0.00556						
concrete compressive strength (Pa)	fc	1.6E+07	1.9E+07	2.5E+07	3.0E+07	3.5E+07	4.0E+07	4.5E+07
	fc^0.5	4000	4358.899	5000	5477.226	5916.08	6324.555	6708.204
projectile mass (kg)	M	0.0036						
projectile velocity (m/s)	V	920						
coefficient for concrete penetration	K							
plain concrete		6.36E-04						
normal reinforced concrete		3.39E-04						
special reinforced concrete		2.26E-04						
impact function	G	x/d -1						
projectile nose shape factor	N	1.14						
maximum size of aggregate	a	0.011						
$\frac{x}{d} = \frac{3.5 \times 10^{-4}}{\sqrt{f_c}} \left(\frac{M}{d^3}\right) d^{0.215} V^{1.5} + 0.5$								
	x/d	17.248	15.869	13.898	12.731	11.824	11.092	10.486
penetration depth (m)	x	0.096	0.088	0.077	0.071	0.066	0.062	0.058
$\frac{x}{d} = K\left(\frac{M}{d^3}\right) log10\left(1 + \frac{V^2}{19,974}\right)$								
plain concrete	x	0.12	0.12	0.12	0.12	0.12	0.12	0.12
normal reinforced concrete		0.06	0.06	0.06	0.06	0.06	0.06	0.06
special reinforced concrete		0.04	0.04	0.04	0.04	0.04	0.04	0.04
$G = 3.8 \times 10^{-5} \frac{N \times M}{d\sqrt{f_c}} \left(\frac{V}{d}\right)^{1.8}$ $G = \left(\frac{x}{2d}\right)^2$ for $\frac{x}{d} \le 2$; $\frac{x}{d} = 2G^{0.5}$ for $G \ge 1$ $G = \frac{x}{d} - 1$ for $\frac{x}{d} > 2$; $\frac{x}{d} = G+1$ for $G < 1$								
penetration depth (m)	x	0.102	0.094	0.083	0.076	0.071	0.067	0.063
$\frac{x}{d} = \frac{2.61}{\sqrt{f_c}} \left(\frac{M}{d^3}\right) \left(\frac{d}{a}\right)^{0.1} \left(\frac{V}{533.4}\right)^n$								
n = 10.7/(f'c^0.5)	n	0.002675	0.002455	0.00214	0.001954	0.001809	0.001692	0.001595
	x	0.071078	0.065218	0.056846	0.051888	0.048035	0.04493	0.042358



APPENDIX C – Additional Images

Figure C1: Sieves (mm), Top - 9.5, 6.7, 4.75

Middle – 2.36, 1.18, 0.6

Bottom – 0.3, 0.15, 0.075

Figure C2: Sieve Pan

Figure C3: Compression tests Control – CC (L), CD (M),CA (R)

Figure C4: Compression test 1% FRC – 1D and 1C

Figure C5: Tensile test Control – CB, CC, CD

Figure C6: tensile test 1% FRC – 1D