protection against Secondary Fragmentation from AP Mines based on natural fibre composites

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The 1997 Ottawa Convention[1] defines a mine as "a munition designed to be placed under or near the ground or other surface area and to be exploded by the presence, proximity or contact of person or a vehicle." An AP mine is defined as "a mine designed to be exploded by the presence, proximity or contact of a person and that will incapacitate, injure or kill one or more persons."

AP mines are either fragmentation or blast types and are equipped with high explosives (chemicals that can detonate[2]). Fragmentation mines (such as POMZ [75 g TNT]) are normally triggered by a tripwire and project metal shards at very high speeds toward the victim. Ballistic threats to personnel are caused by fragmentation as opposed to blast effects.[3] Blast mines (e.g., PMN [40 g TNT]) cause injuries through direct or indirect blast effects. Direct blast effects are those involving changes in environmental pressure due to the occurrence of an air blast. Blast waves may therefore cause injuries to a deminer through overpressure. On the other hand, blast effects can be subdivided into secondary effects, tertiary effects (whole body displacement) and miscellaneous effects (e.g., dust).[4]

Secondary effects include secondary fragmentation from mine blast casing, inner mine components, scree, surrounding dirt, gravel, fragmented demining tools (such as those depicted in Figure 1), etc., all of which are blasted at the victim at different speeds depending on the mass of the projectiles. The extent of injury depends on the mass, velocity, shape, density and angle of impact of the fragments.[4]

The level of protection provided by an armour composite material depends on its energy absorption capability, which is in turn influenced by the type of reinforcing fibres and fabrics, number of fabric layers, areal density[6] and compressive strength.[7]

The current protective clothing (flak jackets) and rigid armour for deminers are manufactured from high-performance fibres such as aramid (Kevlar®, Twaron®) fibres and their composites respectively. The envisaged benefits of composite materials may not be attained with just one type of fibre. Instead, a hybrid system consisting of different fibre types and/or non-fibre materials such as metals and ceramics may be used to achieve the desired properties. Previous writers have pointed out the benefits of hybridisation.[8–12]

Natural fibres are abundantly available in developing countries. These fibres are cheap and come from renewable resources.[13] This paper investigates the possibility of developing a cheap AP mine-protective composite plate that can be manufactured using locally accessible materials and technology in developing countries. The research focuses more on the threat of secondary fragmentation (primary fragmentation results from fragmentation mines) caused by blast mines because in the countries where demining work is concentrated, most injuries are caused by AP blast mines.

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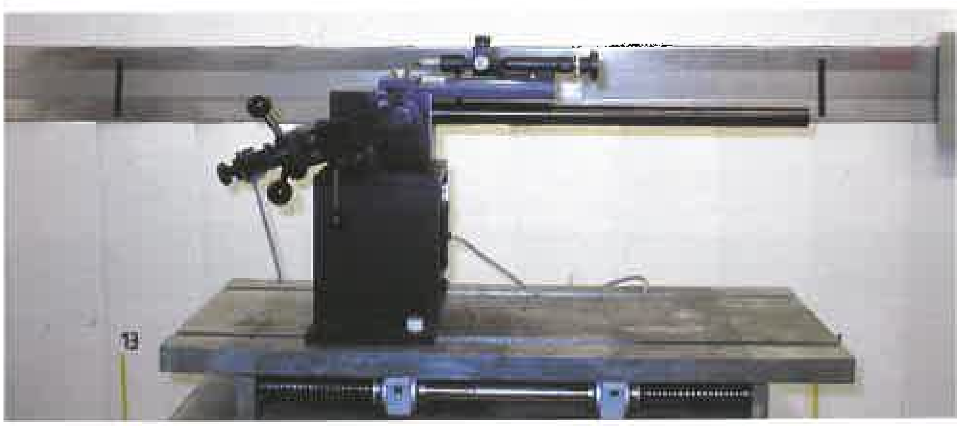
Figure 1 (above): *Typical secondary fragmentation.*[5]

Figure 2 (below): *Block Manometric Cannon Interchangeable (BMCI).*



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Materials and Sample Preparation

Plain woven flax fabric (areal density 280 g/m[2], 10 ends and picks/cm) was purchased from Libeco, Lagae, Meulebeke and Belgium, while polypropylene in sheet form was supplied by Japan GMT Co. Ltd. Details of other natural fibre composites tested in the ballistic study can be found in a paper titled "The Response of Natural Fibre Composites to Ballistic Impact by Fragment-Simulating Projectiles," submitted for publication in *Composite Structures.*

The fabric and polypropylene sheet were cut into 30-cm square pieces that were stacked and wrapped in aluminium foil. The composite samples were processed by compressing the stacking in a compression moulding press at a pressure of 6.4 bar (0.64 MPa) on the material at 190 C for 15 minutes. The resulting fibre volume fraction varied from 46 to 58 percent by reducing the number of polypropylene sheets. The effect of steel was investigated by bonding thin (0.8 and 1.5 mm) mild steel plates onto the composites with epoxy glue.

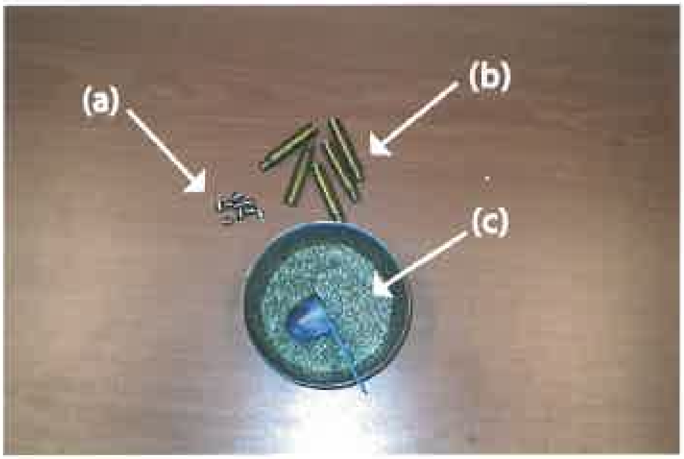

FIGURE 3
(a) Fragment-simulating projectiles (FSPs)
(b) cases
(c) propellant powder

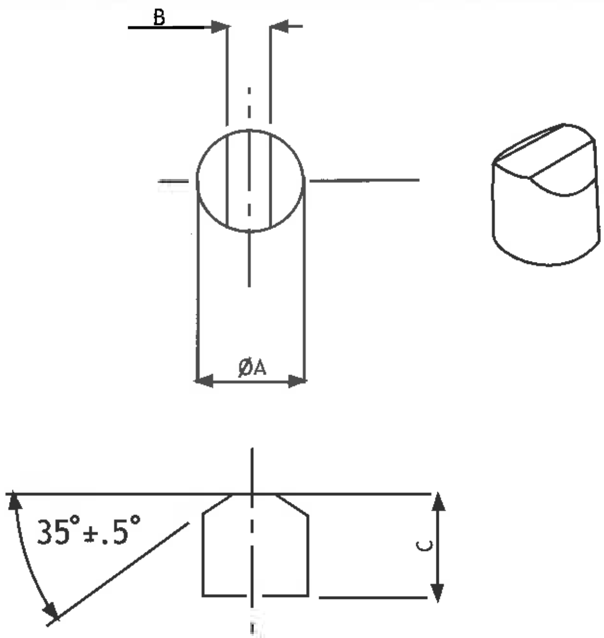

FIGURE 4
Dimensional details of the FSP.
ØA = 5.385 mm
B = 2.54 mm
C = 6.35 mm[14]

Ballistic Testing in the Laboratory

The current standard for measuring the effectiveness of a material against ballistic fragmentation is the North Atlantic Treaty Organization Standardization Agreement (NATO STANAG) 2920.[14] The aim of the STANAG 2920 is the determination of the so-called V_{50} performance. V_{50} is the velocity for which the probability of perforation of the chosen projectile is 0.5. For demining equipment, a V_{50} of 450 m/s related to a fragment-simulating projectile (FSP) of 1.1 g is standard.

The weapon used was a Block Manometric Cannon Interchangeable gun (BMCI) (see FIGURE 2, previous page) and the FSP (FIGURES 3A AND 4) was chisel-nosed, had a diameter of 5.385 mm and was made of alloy steel with a Rockwell hardness of 30∀2. The mass of the FSP was 1.1 g. The propellant used was ball powder 0.50-inch blank and the twist was seven inches per revolution. The room temperature during the tests was maintained at 22 C.

The natural fibre composite panels and composite steel hybrid structures were clamped on a mild steel stand placed 10 m from the weapon. The mean velocity of the projectiles was calculated with the help of a chronometer that measured the projectile flight time between two measuring bases 2 m apart. The projectile impact and residual velocities were required to calculate the amount of kinetic energy absorbed by the target. A Doppler radar antenna linked to a computer was used to determine the velocity of the projectile after perforation.

Results of Laboratory Tests and Discussion

Initial ballistic tests. The results of the ballistic tests are shown in TABLE 1. Whereas the plain flax composites tested did not meet the criteria set by NATO STANAG 2920 (V_{50} = 450 m/s), the composite mild steel hybrids attained a V_{50} of at least 466 m/s. Despite the low V_{50}, the flax composite panels were earmarked for field tests since the envisaged threat and the secondary fragmentation from blast AP mines is considered less than that posed by primary fragmentation from fragmentation mines. Most of the secondary frag-

Sample V_f = 46%	Sample Code	Total Thickness (mm)	Areal Density (kg/m[2])	V_{50} (m/s)
Flax composite	F26	12.9	14.5	312
Flax steel faced hybrid	F26S	14.4	26.3	466
Flax steel faced and backed hybrid	SF26S	14.5	26.7	576
Plain steel	PS	1.5	11.8	264

TABLE 1 (ABOVE): *Results of ballistic tests.*
TABLE 3 (BELOW): *Flax composite and composite/steel hybrids optimised for field tests.*

Code	Material	Flax Fabric Layers	V_f (%)	Thickness (mm)	Areal Density (kg/m[2])	V_{50} (m/s)
F26FT	Flax composite	26	52	9.9	11.3	280
SF26SFT	Composite/ Steel hybrid	26 + steel plates (2 x 0.8 mm)	52	11.6	24.2	489

TABLE 2: *Effect of fibre volume fraction on the flexural modulus of flax composites.*

Fibre Volume Fraction (%)	Flexural Modulus (gpa)
46	5.22 ± 0.13
52	5.83 ± 0.31
55	6.47 ± 0.18
58	5.71 ± 0.16

mentation is usually of much lower density and larger diameter than metallic primary fragments. The irregular shape and larger surface area presented to the armour material further decreases the possibility of its complete penetration of the material.

Optimised solution. The ballistic performance of composites can be improved by processing to high fibre volume fractions. Depending on the application, the most suitable material for ballistic protection provides a good balance among weight, comfort, cost and the level of protection. While it is possible to use very low resin contents in synthetic fibre (e.g., Kevlar®, glass) composites, natural fibre composites presented wetting problems at high fibre volume fractions. A flexural (three-point bending) test was conducted to monitor the bonding at the interface so as to ensure the mechanical integrity of the composite panel. The flexural modulus of the flax composites increased with increasing fibre volume fraction up to V_f = 55 percent, then showed a decrease at V_f = 58 percent as demonstrated in TABLE 2. A fibre volume fraction of 52 percent was utilised in the processing of samples for the field tests. The increase in the fibre volume fraction resulted in a decrease in the composite thickness and areal density (which in turn cause a reduction in the V_{50}). With the said fibre volume fraction (52 percent), the composites presented a good balance among weight, thickness and V_{50}. TABLE 3 presents the parameters of the composite and composite/steel hybrid solution for this research work. These two materials were used for the field tests.

Ballistic Field Testing

Simulated AP mines containing C4 explosives were utilised in the field tests carried out at the NATO test zone at the Houthalen-Helchteren shooting field in Belgium.

Experimental setup. The panel was placed in front of a wooden support fixed to the ground as illustrated in FIGURE 5. The test was conducted using 35 g, 70 g and 150 g of C4 explosives to simulate the small, medium and large AP mines. The explosives were placed in the ground at a distance of 30 and 50 cm (50 cm only for plain composites) from the target and covered with different kinds of projectiles, such as stones, to increase the amount of secondary fragmentation and to simulate demining accidents. The results of the field tests are as summarised in TABLE 4.

Composite/steel hybrids. Two samples were tested at a time at 30 cm and 50 cm respectively from the simulated mine. The distances were measured from the face of the panels to the centre of the simulated mine. These distances were shorter than the representative field operating distances from a mine to the sternum derived from field measurements by deminers, i.e., 65–70 cm.[16] The differences in the distances may produce significant blast effects (pressure has been found to fall as the inverse cube of the distance from the blast[17–19]), but it was assumed that the

FIGURE 5
The field test setup.

FIGURE 6
Front damage on the composites after detonation of 35 g of C4 at 50 cm away.

FIGURE 7
Flax composite front side damage after detonation of 70 g of C4 explosives.

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TABLE 4
Summary of field tests.

Field Test Number	Composite Type (flax)	Test Setup	Distance from Mine (cm)	Mass of C4 Explosives (g)	Result
1a	hybrid	fixed/no back support	30	70	slight debonding
1b	hybrid	fixed/back support	50	70	minor front surface scratches
1c	hybrid	fixed/no back support	30	150	thrown 5 m, debonded
1d	hybrid	fixed/back support	50	150	thrown 2 m, no debonding
2a	composite	fixed/back support	50	35	surface dents fibre fracture
2b	composite	fixed/back support	50	70	fibre fracture, surface dents, crack at rear

differences in the distances selected did not produce a significant change in the velocities of the secondary fragmentation.

The simulated AP mines used for composite steel hybrids contained 70 g and 150 g of C4 explosives to mimic common medium and large AP mines used in many countries. The explosives were placed in two casings of a PMN mine (see FIGURE 5, previous page), which is the largest AP mine, and covered. After detonating high explosive material, almost 100 percent of the energy liberated is transformed into blast energy,[3] which propels secondary fragmentation at high velocities.

Tests using 70 g of C4. Tests on sample SF26SFT, the composite/steel hybrid placed 30 cm from the simulated mine, revealed a small debonding between the front 0.8 mm mild steel plate and the composite at one corner. There was no noticeable damage on the front or rear surface of the material.

Apart from small surface scratches on the front side steel plate, there was no visible damage on sample SF26SFT tested at 50 cm from the simulated mine.

Tests using 150 g of C4. Sample SF26SFT, placed 30 cm from the simulated mine, showed complete debonding of the steel plate on the front side of the composite/steel hybrid system. The debonded steel plate had small dents on the surface. A small debonding between the backside steel plate and the composite was seen at one corner of the composite/steel hybrid system. There was, however, no penetration on the material by a projectile.

Apart from surface scratches, Sample SF26SFT at 50 cm from the simulated mine did not show any penetration or debonding, possibly due to the reduced blast.

Flax fabric reinforced polypropylene composites—*Tests Using 35 g of C4.* FIGURE 6 (on previous page) demonstrates damage that occurred on the front side of the composite panel after detonation of 35 g of C4 explosives. Numerous surface dents and fibre fractures as a result of projectile hits were clearly visible. One projectile caused barely visible damage at the back side of the composite. No complete projectile penetration was observed.

Flax fabric reinforced polypropylene composites—*Tests Using 70 g of C4.* Visual observation after detonation of the 70 g of C4 explosives indicated fibre failure and numerous dents (sizes ranging from small to large) on the front side of the flax composites as shown in FIGURE 7 (on previous page). Several areas of visible damage were observed at the back of the plate. There was also a nearly transverse crack at the back of the composite; however, none of the projectiles was very close to the actual penetration.

These tests show that in order to protect a deminer against secondary fragmentation from small to medium AP blast mines, a natural fibre composite protective material with a V_{50} less than the standard 450 m/s may be sufficient. For large AP mines, a composite steel hybrid system may provide the required protection, but care should be taken to prevent possible injury from steel plates in case they debond.

Conclusions

In this paper, it has been shown that composites based on natural fibres can be alternative materials for anti-ballistic protection against secondary fragmentation in situations of detection and clearance of AP landmines (blast types). The performance per areal weight, both in terms of V_{50} and critical absorbed energy at penetration, reaches the highest value when the natural fibre composites are covered at the front and back with thin (0.8-mm) steel plates.

It is most probable that even better solutions exist using high-tech aramid fibres or special ballistic steels, but these materials are very expensive for people in developing countries threatened by landmines. Composite materials based on readily available natural fibres and commodity polypropylene, faced with cheap mild steel plates, could be a possible alternative. Field tests have been carried out and the preliminary results support this conclusion. ❖

See "References and Endnotes" on page 109

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Clear Path International CD to Benefit Landmine Survivors

In May 2005, in coordination with the 30th anniversary of the end of the Vietnam War, a CD entitled *Too Many Years: A Benefit for Clear Path International* was released featuring such artists as Natalie Merchant, Philip Glass, Juliana Hatfield and The String Cheese Incident. These artists have all responded to the landmine situation in Vietnam by contributing songs for this CD. Approximately 100,000 Vietnamese have been injured and 40,000 killed by landmines since the end of the Vietnam War. Profits from the CD will assist landmine victims. Clear Path International aids landmine survivors in Vietnam and Cambodia and on the Thai-Burma border by providing medical, social and technical support to the families and hospitals. The CD is available for purchase at www.cpi.org.

New Explosive Detector Developed

A team from the Massachusetts Institute of Technology in Cambridge has developed a new explosive detector that is up to 30 times more sensitive to landmines and explosives than mine detecting dogs (MDDs). As of now, MDDs are the most capable mine detectors. This new detector, which works at a distance of well over 30 feet, incorporates a laser to increase sensitivity and is able to detect a femtogram of explosive fumes if the mine is buried. The polymers used in the laser become less fluorescent when they come into contact with molecules discharged by explosive devices. Without the laser, sensors can still detect landmines above ground.