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Energy Absorption and Dynamic Deformation of Backing Material for Ballistic Evaluation of Body Armour

Debarati Bhattacharjee*, Ajay Kumar, and Ipsita Biswas

Terminal Ballistics Research Laboratory, Chandigarh

E-mail: debarati.bhattacharjee@gmail.com

ABSTRACT

The measurement of back face signature (BFS) or behind armour blunt trauma (BABT) is a critical aspect of ballistic evaluation of body armour. BFS is the impact experienced by the armour wearing body, when subjected to a non-penetrating projectile. Mineral or polymeric clay is used to measure the BFS. In addition to stopping the projectile, the body armour can be used only when the BFS also falls within permissible limits. The extent of the BFS depends upon the behavior of the backing material in different loading conditions and prior history. This paper explains some of the studies carried out on the backing material used for ballistic evaluation in Terminal Ballistics Research Laboratory, Chandigarh. It has been observed that the backing material is highly non-linear viscoelastic in nature. The depth of deformation is also linearly proportional to the impact energy and temperature. The effect of time on the depth of deformation is gradual and does not influence the BFS values during a standard ballistic evaluation comprising of 6-8 shots.

Keywords: Backing material, plasticine, back face signature, body armour, ballistic evaluation

NOMENCLATURE

σ	Shear stress (Pa)
σ_0	Shear stress amplitude (Pa)
γ	Shear strain (%)
γ_0	Shear strain amplitude (%)
ω	Angular frequency (Hz)
t	Time (s)
δ	Phase lag
η^*	Complex viscosity (Pa.s)
G'	Storage modulus (Pa)
G''	Loss modulus (Pa)

1. INTRODUCTION

1.1 Blunt Trauma Measurement

The blunt trauma or the back face signature is the impact experienced by the body, wearing the armour, when a non-penetrating projectile hits the armour and dissipates its kinetic energy. The amount of impact force experienced by the body can cause sub-cutaneous damage like bruises and lacerations or sometimes high enough to cause fatal damage to the internal organs. The impact energy on the armour by a non-perforating projectile is dissipated on the rear side which causes a dynamic deformation. Depending upon the properties of the materials used in the body armour, the extent of back face signature varies from armour to armour. Measurement of back face signature is, therefore, an important aspect of ballistic evaluation. During ballistic evaluation, it is not only important to check the perforation of the armour against the projectile but also to ensure that the blunt trauma stays within the permissible limits. Back face signature (BFS) or behind armour blunt trauma (BABT) is a measure of the blunt trauma risk assessment.

Before 1970s, the deformation testing of armours were carried out using 20 per cent ballistic gelatin as a backing material. However, this required the use of high-speed photography to record the deformation as the gelatin, being highly elastic would come to its original position after the firing. Therefore, need was felt to find or develop an easily deformable material that would retain its deformed shape. A number of materials were tested to duplicate the response of the blunt trauma of goat thorax when fired with a 200 g, 80 mm, hemispherical impactor with impact velocity[1] of 55 m/s. It was found that Roma Plastilina#1clay had deformation depth response similar to that of ballistic gelatin. Since then, polymeric and mineral clays have been used as backing materials to measure the BABT or BFS of body armour.

1.2 Backing Material Characteristics

The main purposes of backing material are, (a) to mark the extent of BFS during ballistic evaluation[2] and, (b) to simulate the tissue response appropriately beneath the point of impact, so that the BFS can be correlated to human injury to some extent. Backing materials used during ballistic evaluation are generally oil based non-firing clays which soften on exposure to temperature, and exhibit shear thinning and thixotropic properties. These can be mineral clay where one of the main components is Kaolin, minerals or polymer clay which use petroleum jelly, long chain aliphatic acids. However, as these are commercial materials, their exact composition is undisclosed and keep changing with time. The rheological and mechanical properties of these materials are determined by the composition

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and additives used (pigments, antioxidants etc.). Prior usage of the backing material also changes its subsequent properties because of thixotropicity. The knowledge of the behaviour of the backing material helps in understanding its behaviour under thermal and shear loads and also its service period. The thermo-physiological properties of Roma Plastilina #1 and its behavior with the fixture walls have been explained in detail by Bentz[3], *et. al.* The behavior of the same material upon blunt projectile impact and constitutive relations to obtain the quasi-static mechanical properties have been reported by Munusamy and Barton[4].

The acceptance criteria of a body armour during ballistic evaluation comprise of perforation and back face signature (P-BFS criterion) in which the body armour not only has to withstand the projectile relevant to the threat level, but also keep the back face signature well below the permissible limits. This makes the measurement of back face signature a very critical factor in any ballistic evaluation. The inherent variations in the backing material also play an important role in retaining the extent of the back face signature. Due to these reasons, there was a need to understand the dynamic rheology and the effect of environmental loading on the backing material. This paper provides a study conducted on the backing material used for ballistic evaluation at the Terminal Ballistics Research Laboratory (TBRL), Chandigarh.

2. MATERIALS AND METHODS

2.1 Backing Material

The backing material used for ballistic evaluation can be either mineral or polymeric clay. In TBRL, polymeric clay or plasticine is used as the backing material. Plasticine is mainly oil based modelling clay made of calcium salts, petroleum jelly, long chain aliphatic acids and some colour additives. To make the backing material, approximately 60 kg - 70 kg of modelling clay is taken and heated to a temperature of 35 °C for a few hours to make it pliable. The clay is, then filled into the backing material fixture (a wooden block of dimensions 610 mm × 610 mm × 140 mm). The clay is worked upon using hands or beaters to remove any air pockets inside and ensure uniform consistency and density throughout the block. The block is then continuously conditioned and beaten to remove excess oil and make the material pliable. The consistency and readiness of the clay for use in ballistic material is checked using the process given in National Institute of Justice (NIJ) Standard for Ballistic Resistance of Body Armour[5], NIJ 0101.06.The clay used for backing material is conditioned and handled to make a block free of any voids. The front surface is kept smooth and even with the reference plane which is defined by the edges of the fixture. The material is conditioned *in-situ* using a heated chamber. The consistency and homogeneity is checked by dropping a 1.043 kg steel sphere from a height of 2.0 m at five different places of the backing material. As per the standards, the average indentation of the five drops should be 19±2 mm. The final form of the backing material fixture after calibration test is shown in Fig. 1.

2.2 Viscoelastic Behaviour

Plasticine is essentially a viscoelastic material which is defined by the storage modulus and loss modulus. The dynamic behaviour of the material can be described by a linear isotropic viscoelastic model with complex moduli of tensile and shear stress[6]. These values depend not only on frequency and temperature but also on the prior history of strain deformation. A viscoelastic body produces a strain curve at a phase lag between 0°-90° of the sinusoidal stress applied given by Eqn. (1).

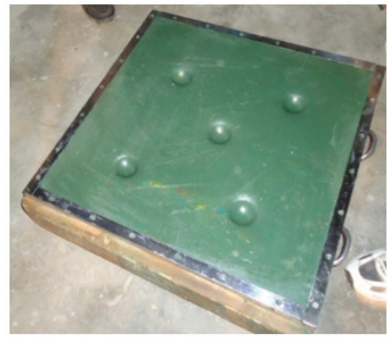

Figure 1. Backing material fixture filled with polymeric clay.

$$\sigma(t) = \gamma_0 [G'' \sin(\omega t) + G' \cos(\omega t)] \quad (1)$$

where $\sigma(t) = \sigma_0 \sin(\omega t + \delta)$, σ_0 is the stress amplitude, ω is the frequency, t is the time, G' is the storage modulus, G'' is the loss modulus, γ_0 is the shear strain amplitude, δ is the phase lag. During the course of complete oscillation, part of the energy is stored elastically which is characterized by storage modulus G', part is irrecoverably lost characterized by loss modulus G''. Another important factor is the phase lag which is given as

$$\tan \delta = G''/ G' \quad (2)$$

This value is also known as the loss factor or damping and gives an idea about the energy absorption properties of the material. The values of tan δ for various classes of materials are given below:

Glass	:	$\tan \delta < 0.01$
Rubber	:	$\tan \delta \approx 1.0$
Viscous	:	$\tan \delta > 1.0$
Fluids	:	$\tan \delta >> 1.0$

The typical response of a viscoelastic material to rheological experiment comprises of its behavior both at high and low frequencies. At high frequencies (short time response), the elastic modulus is dominant and the material is characterized as Elastic[7]. At low frequencies (long time response), the loss modulus is dominant and the material is characterized as Viscous. The system can be characterized by the complex viscosity $\eta^*(\omega)$ which is given as Eqn (3)[8] .

$$\eta^*(\omega) = \sqrt{(G'^2 + G''^2)} / \omega \quad (3)$$

The viscosity is meaningful and is characterized as kinematic viscosity only when $G''>>G'$

2.3 Dynamic Mechanical Analysis

Dynamic mechanical analysis is used to study the material's response to stress, temperature and frequency. An oscillatory load at a set frequency is applied to the material. This technique is more helpful than constant shear methods as the intermolecular and inter-particle forces of the material can be analysed without destroying the structure of the material as the test is conducted at very low shear rates. Mezger[9] defines the two-plate model to explain oscillatory tests. The oscillations of the upper plate are produced by a turning wheel on which a push rod is connected eccentrically. The other end of the rod is attached to the upper plate. When the driving wheel turns, the upper plate is moved back and forth, while the lower plate is immovable. This causes shearing of the sample which is placed between the two plates. When the wheel makes one full turn, it describes an angle of rotation of 360°, corresponding to the duration of one complete oscillation period (Fig. 2). Anton Paar Modular Compact Rheometer Series 302 was used to measure the rheology of the material. The plasticine was taken from two different blocks of backing material and tested for complex viscosity η*, storage modulus G′ and loss modulus G″. Originally, the linear viscoelasticity region (LVER) was checked by testing the material at different shear amplitudes. The visocleastic parameters was checked at nominal angular frequency of 0.1 to 200 rad/sec at three different temperatures viz. 30 °C, 40 °C, and 50 °C.

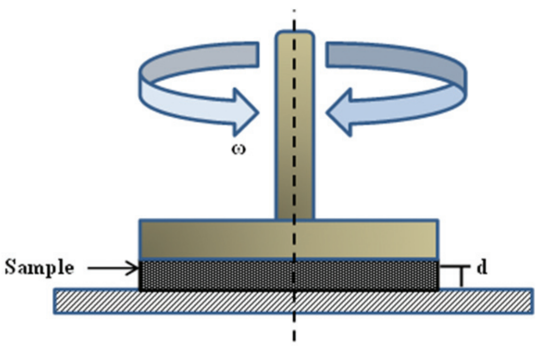

Figure 2. Schematic of two-plate method of oscillatory shear loading, *d* is the thickness of the sample.

2.4 Effect of Impact Energy and Environmental Conditions

The deformation in the backing material was observed with respect to the energy of impact, temperature and time of the backing material. To change the energy of impact, a solid steel ball weighing 1.043 kg with diameter 63 mm was dropped on the backing material fixture filled with clay from different heights. In case of change in temperature, the fixture was kept in a conditioning oven at predetermined temperatures. The measurement of temperature was taken by inserting a temperature probe upto a depth of 51 mm at five places in the block to ensure uniform temperature throughout the block. To observe the effect of time, the backing material was first conditioned as per the NIJ standards[5] and subsequently kept in room temperature and the depth of deformation was checked at regular intervals. In all the cases, the depth of deformation was measured after dropping the same steel ball from a constant height of 2 m.

3. RESULTS AND DISCUSSIONS

3.1 Rheological Studies on Backing Material

Before making detailed dynamic measurements to probe the sample's structure, the linear viscoelastic region (LVER) is required to be defined first. This is determined by performing an amplitude sweep. The LVER also gives an idea about the stability of the sample's structure. The LVER was found to be somewhere between the shear strain values of 0.005 - 0.01% at all the three temperatures corresponding to stress values of 1.34 – 4 Pa. At strains higher than 0.01%, the structure of the material breaks down catastrophically. Figure 3 gives the viscoelastic behavior of the backing material at different temperatures. It is observed that at low as well as high frequencies, in all temperature ranges, G′< G″. There is a dip in the loss modulus at 2-3 Hz where the storage and loss modulus are nearly equal, this means that the material is neither elastic nor viscous. However, at 40 °C, some elastic behavior is observed at frequencies 1-10 Hz but it is not substantially high hence no inference could be made. However, with increase in frequencies (corresponding to shorter time), G′<<G″i.e viscous behavior dominates.

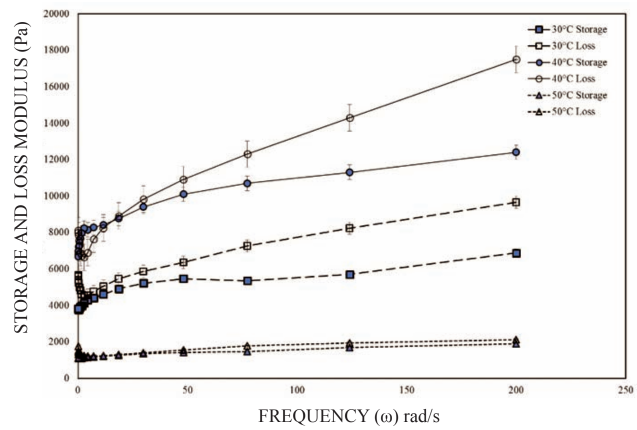

Figure 3. Change in storage and loss modulus with frequency in various temperatures.

Figure 4 which shows the effect in loss factor with frequency for different temperatures. It can be seen that the response is highly non-linear. In non-linear viscoelastic materials, increasing the strain amplitude leads to structural changes which makes the behavior non-sinusoidal. Hence G′, G″ and tan δ are not meaningful for such responses[10].

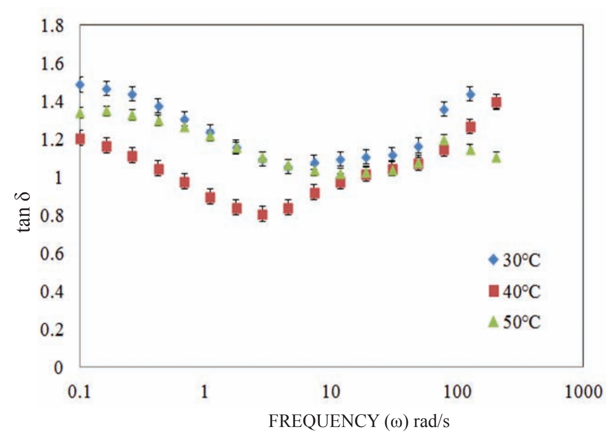

Figure 4. Change in loss factor with respect to temperature.

3.2 Effect of Impact Energy and Environmental Conditions

Figure 5 gives the effect of impact energy on the depth of deformation of plasticine for both the backing material fixture blocks. It was observed that there is a linear relationship between the depth of deformation and the impact energy. However, this relationship exists at very low velocities of impact. The depth of deformation was measured up to a velocity of 11 m/s corresponding to height of 6 m. The behavior at high speed impacts ranging from 100-800 m/s is yet to be studied.

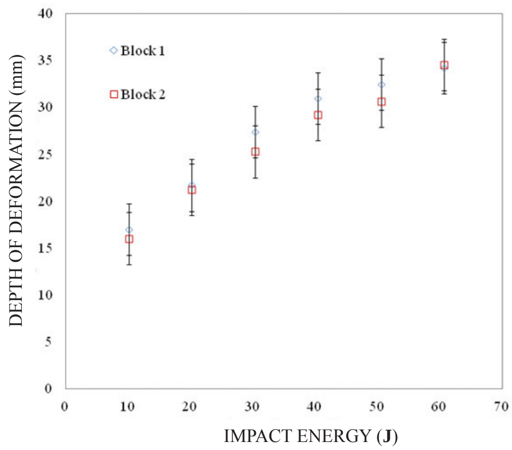

Figure 5. Effect of impact energy on depth of deformation.

Figure 6 gives the effect of temperature on the depth of deformation of the backing material at various stages of heating and cooling modes. The depth of deformation is observed to be marginally higher in the heating mode as compared to the cooling mode. The increase in temperature with respect to time in both heating and cooling modes for two blocks of backing material are given in Table 1.

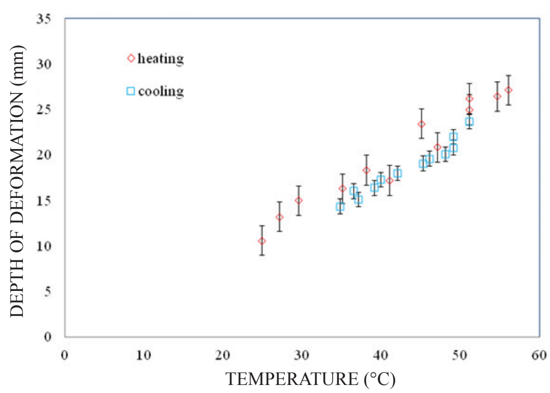

Figure 6. Effect of temperature on depth of deformation.

Table 1. Change in temperature of the backing material during heating and cooling modes

Time (hrs)	Heating mode (increase in temp °C)		Cooling mode (decrease in temp °C)	
	block 1	block 2	block 1	block 2
1	8	4.7	- 3	- 2
2	6	8.5	- 4	- 1
3	6	7	- 3	- 2.8
4	4	6	- 2	- 5.4
5	3.6	5	- 2.3	- 3.4

It can be seen that the decrease in the temperature of the backing material is slower as compared to increase in the temperature. Therefore, it takes less time to reach the temperature required for calibration when the backing material is heated. Figure 7 gives the effect of time on the depth of deformation at a temperature of 23±3 °C. It can be observed that the change in the depth of deformation of the backing material with time is very gradual and remains between 19±2 mm for more than 60 mins. Hence, a single trial, comprising of 6-8 shots that takes around 30-40 mins can be safely carried out in a conditioned backing material without deteriorating its consistency and homogeneity.

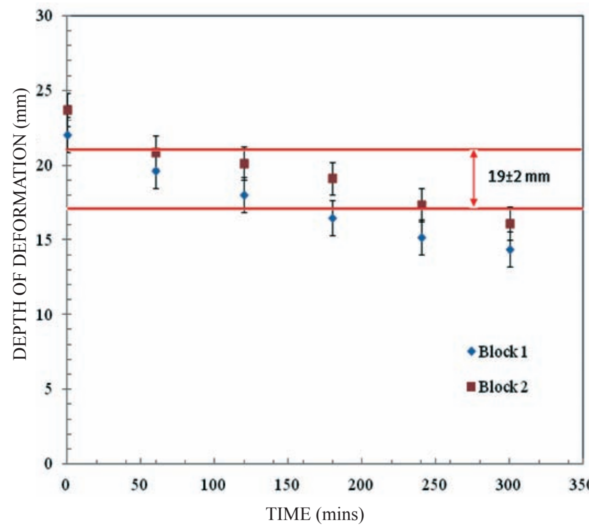

Figure 7. Effect of time on depth of deformation.

4. CONCLUSIONS

Various studies on the energy absorption and effect of external parameters were conducted on the backing material used for ballistic evaluation in Terminal Ballistics Research Laboratory. Rheological studies showed that the material is highly non-linear viscoelastic in nature as the LVE region corresponds to strain values of 0.005-0.01%. The backing material is subjected to much higher stress values in actual conditions. Hence, the material during actual usage is always in non-linear viscoelastic state. For this reason, the common parameters used in characterization like storage and loss moduli, complex viscosity and loss factor are not meaningful in this case.

For low velocity impacts, the deformation of the backing material is linearly proportional to the impact energy. However, in impacts with velocities more than 300 m/s, the behavior of the material is not known. With increase in temperature, increase in depth of deformation was observed. The heating and cooling modes show similar behavior. The material also heats up faster as compared to cooling. It is therefore, advisable to calibrate the backing material with gradual heating mode. The effect of time on the depth of deformation is not sharp and the backing material remains consistent and calibrated with required values of deformation for more than 60 min. This means that a complete trial comprising of 6-8 shots can be safely carried out for 30-40 min without the requirement of a post test drop calibration.

This study gives some information regarding the behavior of the backing material used for ballistic evaluation. However, more studies are required to understand the structural properties of various viscoelastic materials used during ballistic evaluation, their ageing and degradation behavior and the effect of these phenomena on the depth of deformation. This will help in standardization of the backing material and provide a consistent measure of behind armour blunt trauma.

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CONTRIBUTORS

Dr Debarati Bhattacharjee, received her PhD (Textile Engineering) from the Indian Institute of Technology (IIT) Delhi. She is currently working as a Scientist 'D' at Terminal Ballistics Research Laboratory, Chandigarh. She is involved in ballistic evaluation of armour systems. Her areas of interest are : Textile and hybrid systems for high performance applications, advanced armour materials, and artificial neural networks.

Mr Ajay Kumar, obtained his BSc and MSc (Physics) from Chaudhary Charan Singh University, Meerut, in 1995 and 1997, respectively. He has also obtained MTech (Nanoscience and Nanotechnology) from Panjab University, Chandigarh in 2011. He is presently working as Technical Officer 'A' at Terminal Ballistic Research Laboratory, Chandigarh. He has published 6 research/technical papers.

Ms Ipsita Biswas, obtained her MSc (Applied Mathematics) from Jadavpur University. She is currently working as Scientist 'F' and Joint Director of Ballistic Evaluation of Materials and High Strain Rate Studies Group at Terminal Ballistic Research Laboratory, Chandigarh. Her areas of interest are : High velocity impact phenomena on armour materials, high caliber shells, and warhead effectiveness.