CHARACTERISATION OF HUMAN TISSUES ANALOGUES FOR BALLISTIC TESTING

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Abstract

Ballistic testing necessarily employs simulant target materials for ethical and fiscal reasons. Current tissue analogues utilised for ballistic testing / research are, however, typically relatively simplistic – such as ballistics soap or gelatin. Consequently, these materials are seldom representative of complex mammalian constructs. In this paper the authors have drawn together core elements of previously published in-house research with the aim of providing insight into potential approaches to create a composite simulant solution. In particular, tissue analogues covering the epidermal, epithelial, connective, muscular and skeletal components are presented. These results highlight the complementary nature of employing a range of tissue simulant materials and, in parallel, the importance – if ballistic testing data is to be truly representative – of fully understanding the nature of the analogues employed.

1. Introduction

Whether its ballistic testing, vibration analysis or any other type of research that involves human body response, synthetic materials (tissue simulants or analogues) are used to mimic the behaviour of human tissues. Human tissue analogues / simulants are very well known within the research domains of ballistics testing, vibration analysis, forensic etc. (Appleby-Thomas et al., 2018; Hes et al., 2023). There are multiple reasons for using human tissue analogues; ethical, safety, repeatability, reproducibility, availability, cost, ease of use within analysis techniques, and controlled experimental parameters. While this is primarily driven by the fact that working on live mammalian tissues raises significant ethical and safety concerns, another important factor in experiments is their repeatability. Essentially, if simulants

Presented at the 56th United Kingdom Conference on Human Responses to Vibration, held at the Institute of Naval Medicine, Gosport, PO12 2DL, England, 29 – 31 August 2023

are to be useful it must be possible to maintain the same standard and uniform mechanical properties across different samples to enable fair comparison across different tests. Human tissue analogues also offer a cost-effective alternative to live human tissue, particularly if they can also be easily produced and stored within controlled environments. In addition, the transparent nature of selected analogues can allow different analysis techniques to capture the internal dynamics, something otherwise not possible with real-world tissues (Appleby-Thomas et al., 2018; Comley and Fleck 2010; Mabbott et al., 2013; Jussila et al., 2015; Nicholas and Welsch, 2004; Wilgeroth et al., 2012).

There are a number of tissue analogues which have been employed and are discussed here. Gelatin is either a transparent or translucent material that mimics the mechanical properties, viscosity and density of human tissues. It is mainly composed of water and gelatin powder, but sometimes other additives are added for stability. Perma gel® has very similar properties as that of 10 wt% gelatin. In addition, it does not decompose at room temperature, usefully also remaining highly transparent and reusable after melting. Sylgard, in contrast, has an impact response that is heavily dependent on its composition; In this study Sylgard's 527 Silicone Dielectric Gel (Dow Corning, USA) mixed at a 50:50 ratio is used. Whereas Ballistic soap is composed of a soap base, water and additive to achieve similarity in consistency to human tissues. Moving to skeletal analogues, Synbone® is composed of polymers, fillers, and additives to simulate properties that closely resemble natural bone in terms of density, strength, and elasticity. Finally, porcine tissues have been widely employed as human tissue substitutes in-line with the similarities in anatomies between the two species – specifically swine muscle tissue (Appleby-Thomas et al., 2018). However, this latter simulant (as with gelatine which is typically porcine) can have its own ethical implications being animal derived. In this paper, a whole range of tissue simulant data (based on previously published in-house work) is drawn together for the first time with the aim of enhancing the opportunity of creating effective composite analogue solutions (Appleby-Thomas et al., 2018; Appleby-Thomas et al., 2017; Appleby-Thomas et al., 2016; Appleby-Thomas et al., 2016; Appleby-Thomas et al., 2014; Appleby-Thomas et al., 2011; Appleby-Thomas et al., 2011; Shepherd et al., 2011; Wilgeroth et al., 2012; Shepherd et al., 2009).

Individually all the simulants are simplified representations of mammalian (human) tissues. However, to capture all the factors including organs, bones, variation in tissue densities, blood vessels, nerves, etc, it is important to move towards a more complex model that utilises multiple analogues to fully understand the behaviour of the projectile penetration dynamics. However, testing itself is expensive in terms of both time and resources. Consequently, if an analogue material is to be effective it's dynamic properties must be fully characterised to facilitate both numerical simulation of its behaviour and subsequent practical validation.

2. Methodology

The core material characterisation was undertaken dynamically via plate-impact experiments (Appleby-Thomas et al., 2011; Field et al., 2004; Meyers, 1994) which impart shock waves into target materials. This was achieved by using a 50-mm bore single-stage gas gun to accelerate Al and Cu flyer plates into instrumented targets. By ensuring that all impact and target faces perpendicular to the impact axis were planar and parallel to each other, it was possible to allow all elements of the projectile's surface to make

contact with the target essentially simultaneously. Shock propagation was monitored via embedded manganin stress gauges manufactured by Vishay Micro-Measurements, USA. Here data from longitudinal gauges of type LM-SS-125CH-048 is presented. The generic experimental arrangement for plate-impact experiments is shown in Figure 1.

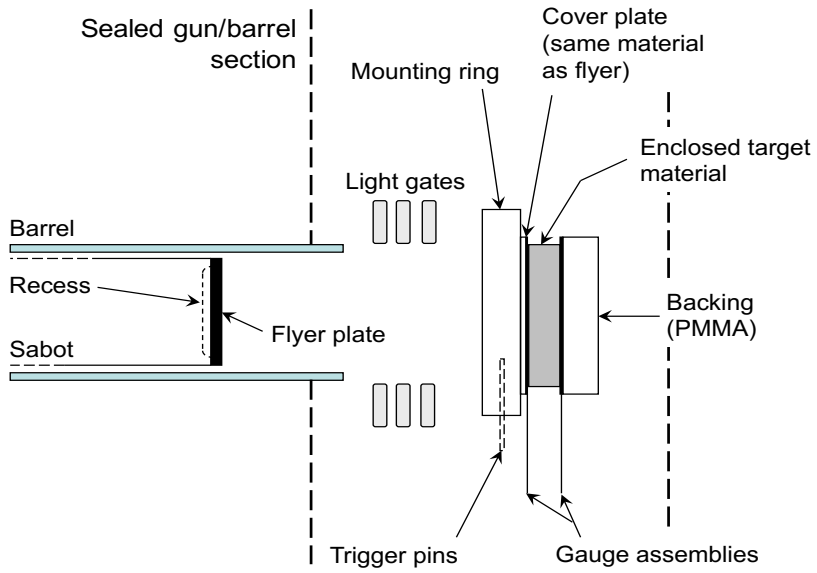


Figure 1. Schematic illustration of typical experimental setup.

A typical set of front / rear gauge traces are presented in Figure 2, with shock velocity (U_s) derived from knowledge of the gauge separation and the different shock arrival times (ΔT in Figure 2). In turn, the gauges themselves provide a direct measurement of stress (σ_x). When combined with the measured impact velocity and known impactor Hugoniot equation-of-state, particle velocity (u_p) may then be calculated via the impedance matching technique (Meyers, 1994).

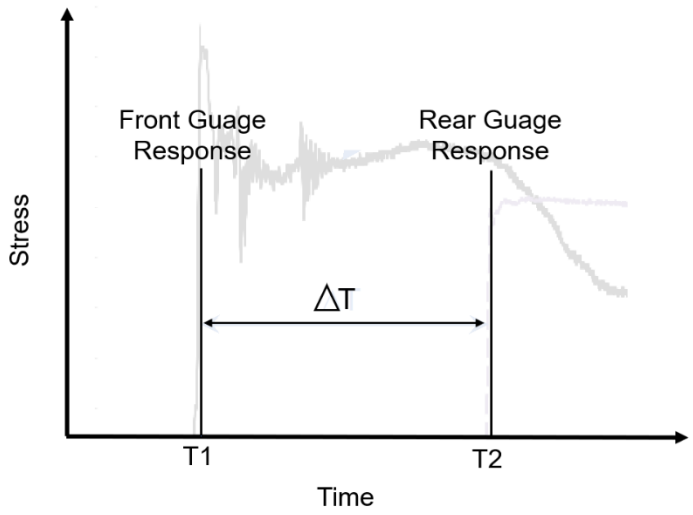
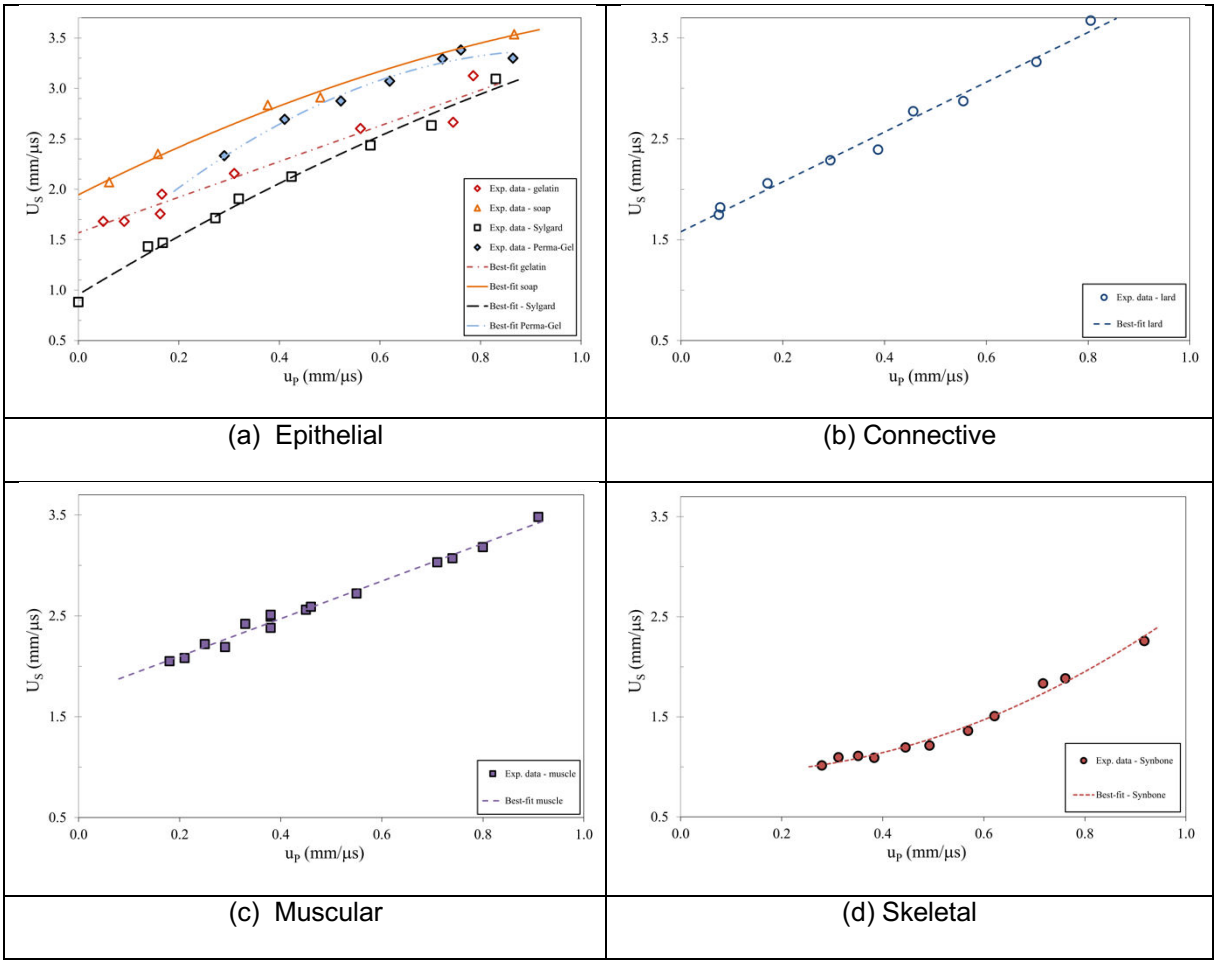


Figure 2. Typical front and rear manganin gauge traces for a 10-mm thick Al flyer impacting a target.

In addition, simulants have been tested against ballistic impacts, projectiles propelled by either propellant or compressed air, to study the penetration characteristics (Mabbot et al., 2013; Hes et al., 2023). Of particular note is recent in-house research that has identified the potential of differing wt.% of gelatine to act as an accurate and repeatable skin simulant (Hes et al., 2023). These authors found that 4-mm thick gelatine was able to replicate v50 velocities (the velocity at which 50% of impactors perforate rather than penetrate a target) ranging from 95 m/s (31 wt.% concentration; (NATO, 2013)) to 150 m/s (Bir, 2012)).

3. Results and Discussion

The behaviour of seven tissue simulants in the U_s-u_p plane is presented in Figure 3, with data separated based on tissue category.



(a) Epithelial | (b) Connective

(c) Muscular | (d) Skeletal

Figure 3. U_s-u_p equations-of-state (including experimental data points) for the seven tissue analogues.

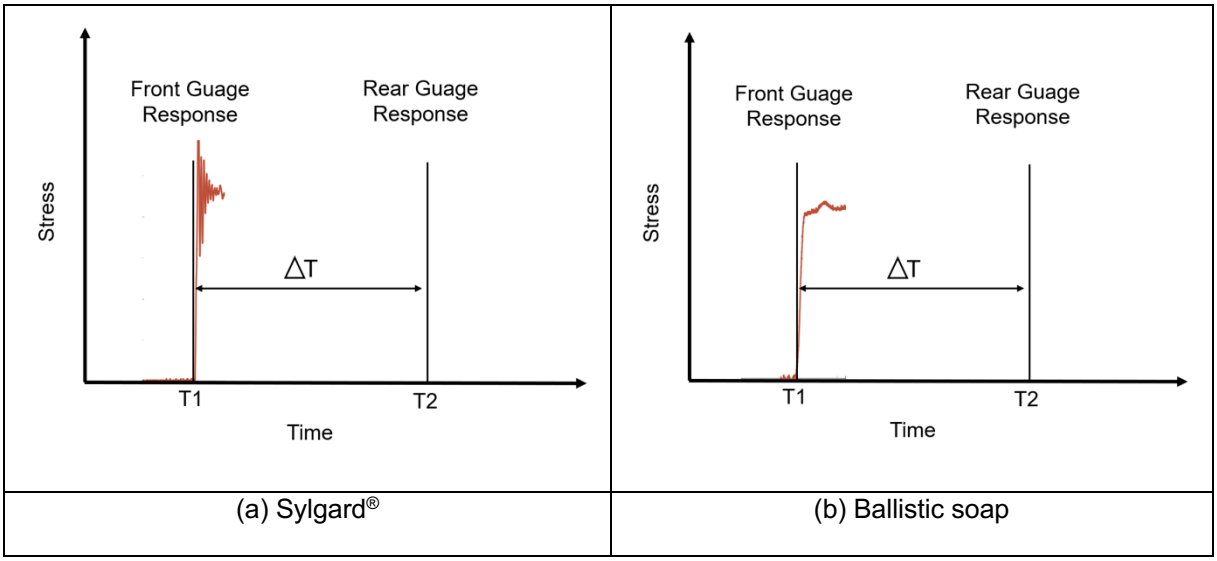
The y-intercept represents the material's bulk sound speed, with the slope linked to material compressibility. For the four epithelial tissue simulants (gelatine, ballistic soap, sylgard®, perma-gel®), there is close agreement in the response at the higher particle impact velocities (>0.7 mm/μs – essentially the ballistic regime) as compared to the lower velocities. Gelatine response is linear across the whole range of velocities, while ballistic soap and sylgard® have a slightly nonlinear response. However, perma-gel® is notably non-linear in the U_s-u_p plane, analogous to the multi-phase behaviour

of polymeric materials seen elsewhere (Porter and Gould, 2006). Overall, this similarity in the behaviour at high particle velocities is also likely linked to the materials polymeric like structure – in this case as the high degree of compression at higher impact velocities may lead to a convergence in shock properties (e.g. impedance) (Appleby-Thomas et al., 2018). There is, however, a remarkable difference in the absolute values of shock velocities between Sylgard (lowest) and ballistics soap (highest) in the low particle velocity regime. This can be correlated to the Young's modulus of the tissues simulants presented in Table 1.

Table 1. Key material properties for the seven tissue simulants considered in this study (data drawn from Refs. (Appleby-Thomas et al., 2011b; Appleby-Thomas et al., 2016a; Appleby-Thomas et al., 2016b; Appleby-Thomas et al., 2017; Wilgeroth et al., 2012).

Human Tissues	**Simulants**	**Elastic Properties**
Epithelial		
Epidermis Dermis Muscle	Gelatin	ρ_0 = 1.06 ± 0.01 g/cc, c_l = 1.48 ± 0.06 mm/μs c_s = 0.33 mm/μs (calc.), **v** = 0.47 (est.), **K** = 2.17 GPa (calc.)
Hypodermis	Sylgard®	ρ_0 = 1.01 ± 0.01 g/cc, c_l = 1.10 ± 0.02 mm/μs c_s = 0.57 ± 0.02 mm/μs, **v** = 0.32 (calc.), **K** = 0.78 GPa (calc.)
Hypodermis	Ballistic soap	ρ_0 = 1.11 ± 0.00 g/cc, c_l = 1.67 mm/μs **cs** = 0.69 mm/μs (calc.), **v** = 0.40 (est.), **K** = 2.39 GPa (calc.)
Epidermis Dermis	Perma-Gel®	ρ_0 = 0.56 ± 0.01 g/cc, c_l = 1.42 ± 0.06 mm/μs c_s = 0.38 ± 0.06 mm/μs, **v** = 0.46 (calc.), **K** = 1.03 GPa (calc.)
Connective		
Elastic Adipose	Lard	ρ_0 = 0.95 ± 0.01 g/cc, c_l = 1.51 ± 0.10 mm/μs c_s = 0.36 mm/μs (calc.), **v** = 0.47 (est.), **K** = 2.00 GPa (calc.)
Muscular		
Cardiac Smooth Skeletal	Porcine	ρ_0 = 1.09 ± 0.00 g/cc, c_l = 1.93 ± 0.03 mm/μs c_s = 0.89 ± 0.10 mm/μs, **v** = 0.36 (calc.), **K** = 2.90 GPa (calc.)
Skeletal		
Skeletal Bone	Synbone®	ρ_0 = 0.77 ± 0.10 g/cc, c_l = 1.75 ± 0.13 mm/μs c_s = 0.71 ± 0.10 mm/μs, **v** = 0.40 (calc.), **K** = 1.84 GPa (calc.)

Sylgard® has the lowest young modulus (0.78 GPa) and ballistic soap the highest (2.39 GPa). The front gauge response on impact shown in Figure 4 for Sylgard® and ballistic soap clearly illustrates the two extreme responses; Sylgard® with an underdamped response and ballistic soap with an overdamped response; whereas the other tissue simulant's responses lie between these two extremes. It's apparent that the lard and porcine tissue responses are close to linear, and both lie close to gelatin. However, Synbone® presents a very different response than other tissue simulants because of its complex internal porous structure.



(a) Sylgard®

(b) Ballistic soap

Figure 4. Front manganin gauge response.

Overall, this significant variation in properties clearly highlights the range of properties inherent in what are otherwise relatively conventional tissue analogues. Consequently, this further reinforces the importance of developing composite simulant (analogue) solutions.

As touched on previously, recent in-house research has also suggested that moving away from the conventional wt.% values for gelatine has the potential to allow the material to be utilised as a readily available and skin (epidermal) simulant. Figure 5 illustrates the proposed gelatine concentrations of a 4mm thick sheet, to achieve differing v50 values against standardised Crossman 4.5-mm diam. copper-coated steel ball bearings (Crossman, 2023). This clearly highlights the fact that gelatine – with its ability for properties to be readily varied – holds out significant potential to form multiple elements of a future composite mammalian tissue simulant system.

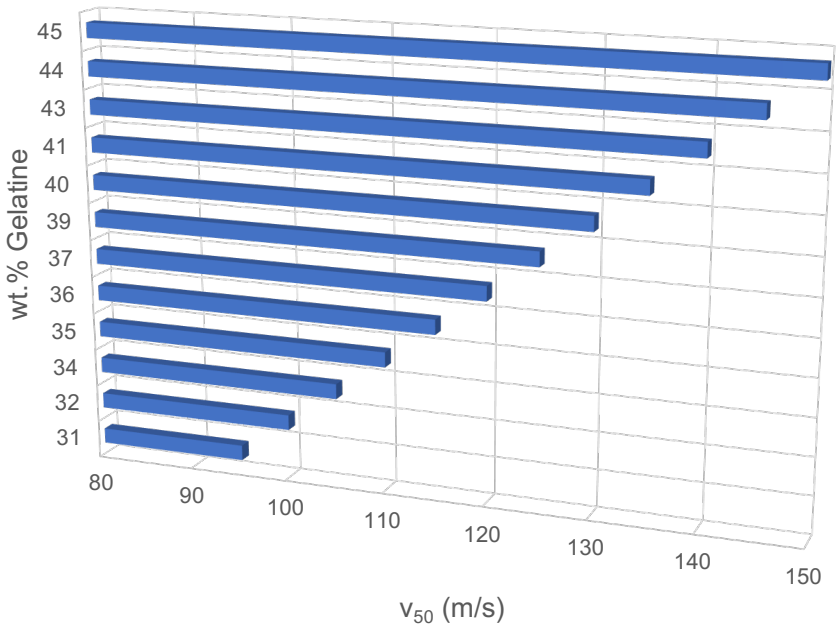


Figure 5. Proposed gelatine concentrations to achieve differing v50 values for a 4mm thick gelatin sheet.

Figure 6 draws together the discussions and results above, illustrating for the first time the concept this research is moving towards – namely creation of a tissue simulants tool kit that – at present – covers ca. 95% of the human body.

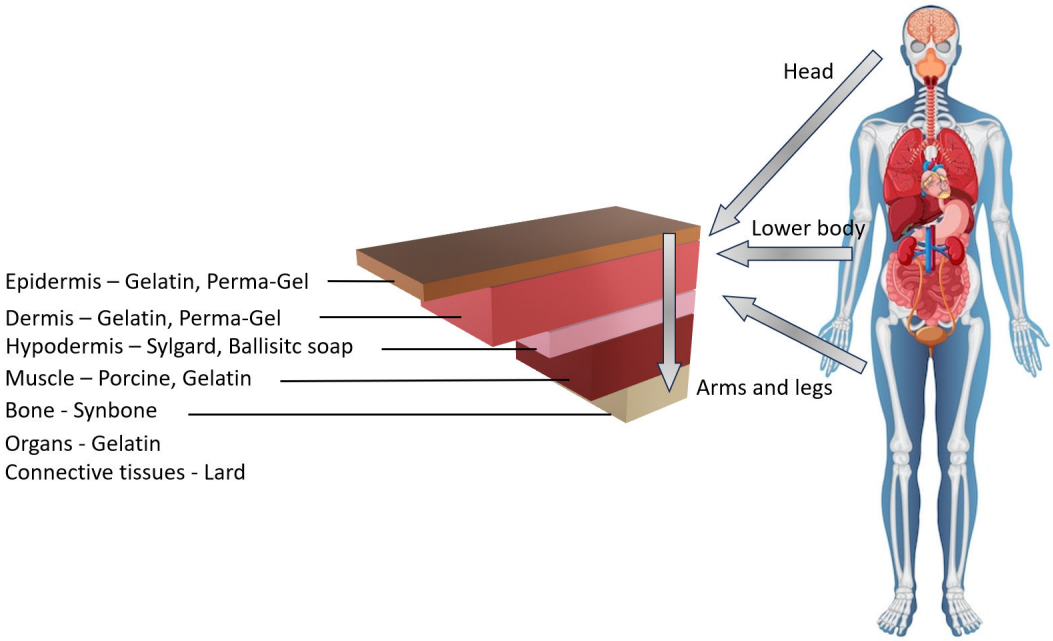


Figure 6. Tissue simulants tool kit that covers 95% of the human body. (Figure modified from [https://www.freepik.com/free-vector/anatomical-structure-human-bodies_26353260.htm])

4. Conclusion

This paper characterises a whole range of tissue analogues based on the work that has been undertaken by the authors previously – drawing this together in the most complete manner to-date. Collectively this research now has the potential to accurately simulate / describe 95% of the key elements of mammalian structures (covering bulk tissues, muscular tissues, skeletal tissues, connective tissues and epidermal tissues), with the exception at the moment of nervous tissue. Importantly, this research provides a tool kit for someone that wants to solve the problems around impact events on tissues in an ethically and fiscally controlled manner. As this data will be useful for anyone in a situation in which there is something which is tissue related, or biological, involved in an impact event it reaches out to areas such as vibration testing, effects of shocks or blasts, shock loading etc.

5. Acknowledgments

The authors would like to acknowledge that data presented in this paper has largely arisen from a number of MSc and PhD research projects conducted at Cranfield University. The contribution of the relevant students is acknowledged as appropriate via the references.

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2023-08-30

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