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Evaluation of materials for potential use as

drop-off mechanisms for avian harnesses

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1.0. Abstract

Bio-logging devices play a crucial role in avian research, deployed on thousands of birds annually to gather data on space use, behaviour, and energetics. Harnesses are commonly used for device attachment, but many lack weak links for controlled detachment, leading to the perpetual carrying of non-functional tags. This thesis focuses on enhancing weak link integration for avian harnesses by evaluating three rubber band types and three adhesives as potential biodegradable components. All materials were subjected to load/shear testing, and survival times were quantified under natural weathering and constant temperatures. Rubber bands were also incorporated into a simple harness deployed on domestic pigeons (*Columba livia*) to quantify survival times on live animals. Survival times were influenced by complex interactions between temperature, humidity and material type. Rubber bands had survival times of 2-143 days, with two band types (TPU and Natural Rubber) appearing to fail at consistent times, suggesting they might perform well as weak links. The breaking stress of rubber bands was strongly dependent on whether they were knotted or unknotted, with knotted bands having lower breaking stress. This highlights that the performance of a rubber band depends on how it is incorporated into a harness. Adhesive shear strength was similar to the breaking strain of rubber bands, but survival times were higher. One adhesive showed a consistent failure time (Evo-Stik ~ 100 days), suggesting this could function well as a weak link. Surprisingly, load was not significant for all rubbers or adhesives. Overall, the results identify two potential rubber bands and one adhesive that appear to have reasonably predictable survival times. These results will hopefully raise awareness of the ability to design low-cost weak-links, enabling high quality data to be collected for a predetermined period, whilst also providing a predictable harness release for the benefit of bird welfare.

Keywords: Adhesive, breaking stress, drop-off mechanism, harness, rubber band.

Declarations and statements

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed [redacted] **Date 05/12/2023**

This work is the result of my own independent study, except where otherwise stated. Other sources are acknowledged by references. A bibliography is appended.

Signed [redacted] **Date 05/12/2023**

I hereby give my consent for my work, if relevant and accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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I hereby confirm that the University's ethical procedures have been followed and, where appropriate, that ethical approval has been granted.

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1.0. Background

Biologging devices have become important tools to research the behaviour, movement and physiology of birds, as well as their responses to environmental change, providing valuable insight into the drivers of species decline, mapping migration and flyways, and highlighting priority areas for conservation (Bedrosian et al. 2015, Hewson et al. 2016, Mancuso et al. 2021, McKinnon and Love 2018, Meier et al. 2015). Researchers have been developing methods to identify and track birds for over two hundred years. As early as 1803 John Audubon experimented with attaching wire leg rings to birds to identify individuals and understand their movements (Audubon 1834). However, it was not until the 1950's, when the transition from the vacuum tube to the miniature transistor meant that radio transmitters were small enough to be attached to birds (Eliassen 1960, LeMunyan et al. 1959). Radio telemetry transformed tagging, as portable receivers could be used to triangulate the signal from a VHF radio transmitter attached to an animal. In 1962 researchers serendipitously created the first telemetry device capable of monitoring the respiration of a free-flying bird (Lord et al. 1962). They encircled a duck's body with a thin metal strap held in place with electrical tape. As the bird flew, distortional variation affected the radio signal, which identified the wing beats and respiratory rate of the bird (Lord et al. 1962). Not only could researchers now track a bird, but they could also monitor physiological parameters.

The development of biologgers has gone hand in hand with the development of attachment methods. One of the most widespread techniques for attaching biologgers is the use of harnesses. Indeed, this is the main attachment type that is used for long-term deployments. In 1963, Cochran specifically designed a body harness of plastic straps to mount a telemetry device to geese (Cochran 1963). Tester then created a new harness with fully adjustable straps that could be modified to suit birds of differing morphology (Tester 1963). In 1968, the same harness design was adapted to fit Barred Owls (*Strix varia*) (Nicholls and Warner 1968) with the objective of creating a lightweight, conforming, comfortable, and secure harness capable of accommodating an aerodynamic transmitter housing, allowing the owls to freely engage in their natural behaviours. This type of body loop harness continues to be used in various forms today.

Harnesses must be robust enough to be able to withstand the challenges posed by the target species according to its size, strength, behaviour and habitat. One of the key factors in harness design is balancing lightweight construction, durability, load capacity (Caccamise and Robert 1985), which has resulted in the frequent use of Teflon® tape (Bally) and Stretch Magic® (Pepperell). However, these materials do not degrade. Most harnesses therefore remain attached to individuals for periods of several years, or even the lifetime of the animal, often outlasting the performance of the tag that they are designed to carry (Bedrosian et al. 2015, Jirinec et al. 2021, Kenward 1987, Legagneux et al. 2013). However, harnesses can have detrimental effects on birds, including physical injury (Dixon et al. 2016, Hurtado et al. 2021, Jirinec et al. 2021, Michael et al. 2013, Paton et al. 2020, Peniche et al. 2011), negative impact on social behaviours, energy expenditure, foraging, breeding and survival (Barron et al. 2010).

To reduce these detrimental long-term effects, mechanisms to enable harnesses to detach have been developed. Researchers often use a degradable material to attach strands of the harness together, theoretically allowing the harness to detach once this material fails, although in practice, this still leads to harnesses being attached for many years, depending on how the degradable material is incorporated . Another approach is the use of a customized weak link in harnesses, which either degrades or can be programmed to detach after a specific period (*Table 1*). Rubber bands (Brust et al. 2019, Kesler 2011, Müller et al. 2018, Netoskie et al. 2023) and cotton thread (Hallworth 2009, Karl and Clout 1987) have frequently been used as weak links for small, flighted birds, due to their low mass.

Table 1. Example of materials commonly used for weak-link drop off harnesses

Material used as weak link	Attachment type	Author/date	Species	Survival time range
Cotton thread 1mm	Tarsal (sewn)	Bedrosian 2005	*Corvus Corax*	41- >60 days
Cotton thread.	Leg loop. Entire harness constructed from thread	Hallworth 2009	*Parkesia motacilla , Cardellina canadensis Cardellina pusilla Acanthagenys rufogularis*	4-6 weeks (estimated)
Cotton thread	Body harness (sewn)	Herring & Gawlik 2010	Dummy bird bodies	> 547 days
Cotton thread	Body harness	Higuchi et al. 2004	*Antigone vipio*	106 - >186 days (based on battery life)
Cotton thread 1 or 2 strands	Body harness	Karl & Clout 1987	*Hemiphaga novaeseelandiae*	3 - >13 months

Cotton thread 4 strands	(threads inside plastic tube)		*Nestor meridionalis*	3-5 months
Cotton thread	Body harness with sewn, overlap	Kruger 2020	*Gypaetus barbatus*	>8 years
Cotton thread	Wing loop harness	Clewley 2021	*Laridae sp.*	1-2 years
Elastic cord 1 mm	Leg loop. Leg loop. Entire harness constructed from	Mong & Sandercock 2007	*Bartramia longicauda*	292-1448
Elastic thread 0.5 mm	Leg loop	Streby et al. 2015	*Seiurus aurocapilla*, *Vermivora chrysoptera*	40-70 days
Polyester thread	Body harness (sewn)	Herring & Gawlik 2010	Dummy bird bodies	> 547 days
Dental floss	Body harness with sewn, overlap	Kruger 2020	*Gypaetus barbatus*	>10 years
Eco balloon ribbon. Dissolvable in water	Tail mounted (tied on)	Evens et al. 2018	*Caprimulgus europaeus*	1-30 days (rain dependent)
Rubber band 1.5 mm	Leg loop(tied & knots strengthened with cyanoacrylate)	Kesler 2011	*Todiramphus gambieri*	30 - >120 days Outliers up to 15 months
Rubber band	Leg Loop tied insert	Netoskie et al. 2023	*Myadestes obscurus*	< 1 year (est.)
Rubber band	Leg loop - entire	Brust et al. 2019	*Turdus sp.*	Few weeks (est.)
Rubber band	Leg loop - entire	Muller et al 2018	*Oenanthe sp.*	Few weeks (est.)

Rubber – section of balloon	Tail mounted	Rutz & Troscianko 2013	*Corvus moneduloides*	5-10 days
Nitrile rubber	Wing loop harness	Clewley 2021	*Laridae sp.*	≤ 4 years
Cotton tape 20mm (rolled and sewn)	Body harness (sewn)	Boshoff et al. 1984	*Gyps coprotheres*	>10 months
Cotton tape 12mm (rolled and sewn)	Body harness (sewn)	Diekmann 2004	*Gyps coprotheres* *Gyps africanus* *Torgos tracheliotos*	3-5 years (estimated)
Cotton cord	Wing loop harness	Clewley 2021	*Laridae sp.*	≤ 4 years
Dissolving suture Vicryl 0.5 mm	Leg loop. Harness constructed from Vicryl.	Doerr & Doerr 2002	*Climacteris picumnus* *Cormobates leucophaea*	28-280 days
Dissolving suture Vicryl 3.5 metric (0.2 mm)	Leg Loop. harness made of Vicryl.	Woolnough et al. 2004	*Sturnus vulgaris*	22-unknown days
Adhesive -Gorilla Super Glue (Cyanoacrylate)	Body harness	Herring & Gawlik 2010	Dummy bird bodies	Super glue survival ranged from 219 to 451 days, depending on combination
Adhesive - Cyanoacrylate	Interscapular mounted cotton cloth	Johnson et al. 1991	*Cyanocitta cristata* *Turdus migratorius,* *Toxostoma rufum* *Cardinalis cardinalis*	1-49 days
Magnesium/copper/ brass washers (electrolytic decay)	Collar	Thalmann 2013	*Sarcophilus harrisii*	71-191 days

More recently, novel degradable materials and techniques have been used, including water-soluble ribbon (Evens et al. 2018), absorbable suture (Doerr and Doerr 2002, Woolnough et al. 2004), balloons (Rutz and Troscianko 2013), dental floss (Krüger 2020), metal washers (Sperling 2004, Thalmann 2013), and electronically operated devices (Rafiq et al. 2019). Yet while weak links have been used in harnesses since the 1980s (Bedrosian 2005, Bedrosian and Craighead 2007, Higuchi et al. 2004, Karl and Clout 1987, McIntyre et al. 2009, Parejo et al. 2015, Rappole and Tipton 1991), they are still not in routine use (Clewley et al. 2021). This is likely related to the paucity of information on the performance of different weak link materials, including, critically, their reliability, and a lack of guidelines to encourage their use (Hawkins 2004, Wilson and McMahon 2006).

1.1. Drop-off harnesses

Refinement of harness design is important not only for capturing accurate data but to meet the standards of the refinement principle from the Three Rs framework (Replacement, Reduction, Refinement), which directs continuous testing and evaluation of biologging protocols for the welfare benefit of the target animal. Initial capture and harness fitting are extremely stressful to a bird and there are many incidents of capture myopathy causing death (Carpenter et al. 1991, Höfle et al. 2004, Marco et al. 2006). If recapture to remove a harness and data logging device can be avoided, it can only be beneficial.

The idea of a weak link is that, after a certain duration, it degrades enough for the whole harness mechanism to fail, and the data logger and harness fall from the animal without causing entrapment. Most systems are based on the passive degradation of the weak link, although active, electronically controlled mechanisms have also been developed (Rafiq et al. 2019). In some circumstances, the whole system can then be retrieved by the researcher and the unit redeployed (Xerius 2016).

There are several considerations for the design of a weak link. First, the incorporation of a weak link must not affect the fit of a harness, as poorly fitting harnesses can result in injury, and even mortality (Hines and Zwickel 1985, Karl and Clout 1987, Kok 2020, Peniche et al. 2011). Harness design and the incorporation of weak links must therefore consider factors including the cyclical weight fluctuations of birds e.g. due to pre-migratory fattening, winter body fat increase in sedentary species or growth of a juvenile (Buck et al. 2021, Lameris et al. 2017, Piersma et al. 1995). Furthermore, it is reasonable to predict that the better the fit of a harness, the less likely animals will be to interfere with it, which could place it under potential stress and risk premature detachment.

Two further, critical, considerations are how and when a harness detaches. The question of "how" relates to how the weak link is incorporated into the harness. This has its own challenges as the weak link should not be readily accessible to the animal, or at least incorporated in a manner that minimize animal interference. It should also be incorporated into the harness in a way that ensures that all harness straps fall away from the bird at the same time when the weak link fails. While a simple harness was designed in this thesis with these requirements in mind, the focus of this thesis is on the selection of weak link materials; when they might be expected to fail, and how this varies with environmental conditions and load.

1.2. Materials for weak links

While researchers have used a range of weak links, there is no comprehensive framework enabling researchers to assess the appropriateness of materials based on their longevity, compatibility with harness designs, and suitability for the environmental conditions in which they are deployed. This is a complex and multi-factorial task. For example, cotton tape used for weak-link harnesses can last for several months, or even years (Boshoff et al. 1984, Diekmann 2004) but it is not strong enough to withstand the beak of vultures without serious consideration to the thickness and placement in the harness design. Furthermore, as cotton biodegrades quickly in a damp environment (Zambrano et al. 2021), thin cotton thread may not be suitable for a long-term study of aquatic birds but could be ideal for short durations.

A necessary first step is therefore to improve the information available to researchers about the performance of materials in a range of conditions (Boshoff et al. 1984). This study was motivated by a specific research paper (Kesler 2011) which presented a comprehensive description of a rubber band employed as a degradable link in a small leg loop harness, which contrasted with other studies that mentioned the use of a generic "rubber band" without providing the type, size, or source of the material. Recognizing the diversity of rubber compositions and acknowledging that terms like "elastic" or "rubber" band encompass a broad range of materials, led to the hypothesis that the degradation rate of these bands would vary based on their chemical composition and the environmental conditions they were subjected to. For instance, rubber materials can be broadly classified into two categories, natural rubber and synthetic rubber, which may differ in their properties and suitability as weak links, despite all being elastomers (a group of flexible polymers). Synthetic rubbers are produced by the polymerization of monomers derived from petroleum or synthesized from thermoplastic or polysiloxanes, whilst natural rubber consists of polymers originating from the organic terpene, isoprene.

Adhesives also have potential to form weak links. For instance, Cyanoacrylate has been trialled in a drop-off mechanism for harnesses (Herring and Gawlik 2010), with mixed results, but there are several other adhesive options, including acrylates, resins, and thermoplastics, which could prove useful, but require testing. Adhesives are substances used to bond items together. Similar to rubber they can be grouped into two types: Natural and synthetic. Natural Adhesives, also known as bio-adhesives or glues, are made from organic sources such as tree resins, vegetable dextrin, from sources such as maize, potato and wheat, or proteins of animal origin e.g. casein, collagen, albumin. Notable glues in this range are made from Isinglass (fish collagen), Gum Arabic (*Acacia sp*. gum), Shellac (*Kerria lacca* insect secretion), hide glue, from connective tissue and hide, and resins, such as pine (*Pinus sp.)* tar. All these adhesives are completely biodegradable in the natural environment, being degraded by fungi, bacteria and yeasts. None of these were used in this study because they are difficult and time consuming to prepare and cure and lack the strength and durability of modern synthetic adhesives.

Synthetic adhesives include elastomeric rubber-based contact adhesives e.g. Evo-Stik Impact; thermoplastic (TPEs) and acrylates, emulsions such as polyvinyl acetate (PVA) and thermosets e.g. epoxy resins, polyurethane and cyanoacrylates. All these adhesives are manufactured from a base of crude oil and although some, such as PVA are water soluble, they still accumulate in aquatic systems. There are also siloxane-based adhesives, which are largely marketed as sealants for the construction and automotive industries due to their covalent Si-O-Si bond with glass. They have excellent chemical and heat resistance.

1.3. Objectives

This thesis aimed to quantify the survival of three different elastomers and three different adhesives as potential materials for harness weak links. When selecting the rubber bands for testing, it was discovered that many commercially available bands did not specify their chemical profile and were generally listed as either ‘latex’ or ‘latex free’. Despite contacting several manufacturers, only three different brands of rubber band could be determined as: Thermoplastic polyurethane (TPU), Silicone Rubber and Natural Rubber. The three adhesives were chosen after researching the chemistry of several commercially available brands. Many adhesives were discovered to be similar and eventually three chemically different adhesives; EvoStik Impact (polychloroprene) UHU Universal (polyacrylate) and Gorilla Contact Clear (polysiloxane) were chosen for testing.

All materials were subjected to load/ shear testing, and survival times were tested in (i) natural weathering in the UK, (ii) constant temperature conditions. Rubber bands were (iii) incorporated in a simple harness deployed on domestic pigeons (*Columba livia*) (this was not feasible for adhesives given the long survival times). The ultimate aim is to provide insight into the most appropriate materials for potential use as weak links in harnesses according to study species, environment and research question, and promote the use of drop-off systems within the biologging community.

The survival times of rubber bands were expected to vary based on their composition and testing conditions. Natural Rubber, owing to its susceptibility to UV light, ozone, and microbial decay, was expected to exhibit a shorter survival time, especially in an outdoor environment. Synthetic elastomers like TPU and Silicone are manufactured for greater stability and should therefore have longer survival times. However, due to the small cross-sectional area of the rubber bands, none were expected to endure beyond a few weeks.

Predicting the survival times of adhesives was more challenging, due to the paucity of comparable testing results, with only one paper detailing cyanoacrylate adhesive lasting >400 days on a harness (Herring and Gawlik 2010). Anecdotally, Evo-Stik Impact, a widely used contact adhesive, was reported to have good bond strength and resistance to heat and water, which made it a plausible candidate for serving as a weak link in harnesses. Silicone adhesives, recognized for their water and heat resistance, may also have had extended survival, but the performance of UHU, an acrylate-type, general purpose adhesive, was difficult to predict.

The survival times for both rubber bands and adhesives were also expected to vary with temperature and humidity. Temperature can affect the rate of chemical reactions and physical processes within these materials, which can influence their mechanical properties and degradation rate (Beatty 1964, Mars and Fatemi 2004, Viana et al. 2017). Similarly, fluctuations in humidity can impact the water content absorbed by rubbers and adhesives, leading to changes in mechanical properties and susceptibility to hydrolysis and oxidation (Ashcroft et al. 2001, Bahrololoumi and Dargazany 2019, Borges et al. 2021, Ossefort and Testroet 1966). The sensitivity to temperature and humidity is likely to vary with material type. For instance, variations in polymer composition, cross-linking density, and filler content among elastomers can lead to distinct responses to environmental conditions. Additionally, the presence of additives, such as plasticizers or stabilizers, may further modulate the materials' sensitivity to temperature and humidity. The rubber bands, being more exposed to environmental conditions, are expected to show greater sensitivity compared to adhesives, which are sandwiched between brass plates.

2.0. Materials and Methods

The design of a harness was a necessary first step, in order to establish how rubber bands and adhesives could potentially be incorporated as weak links. This informed later steps of the experimental design, including the selection of adherends for the adhesive testing.

2.1. Harness design

The harnesses were tested on domestic pigeons (*Columba livia domestica*) housed at Swansea University. It was determined that leg loops, which are commonly used in harness designs, were not suitable for this particular species due to the pigeons' short femur and covered knee. Consequently, the leg loops could not be positioned sufficiently high on the leg to properly fit over the synsacrum without the addition of an extra waist loop. Previous experimentation with this modified design had resulted in injury to the subjects.(Irvine et al. 2007). Therefore, a simple wing loop, with a single point of articulation that sat over the interscapular area *(Figs. 1 a & b)* was designed to test survival.

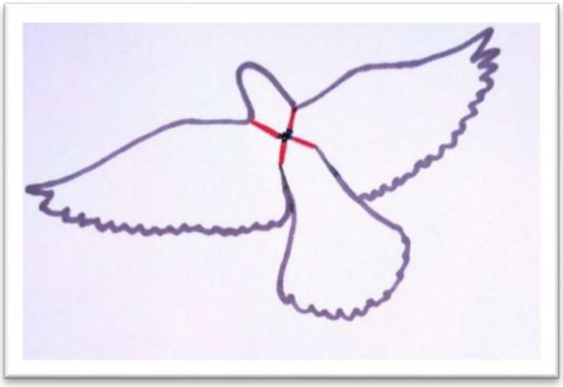

Fig. 1a. Dorsal view of the fitted harness.

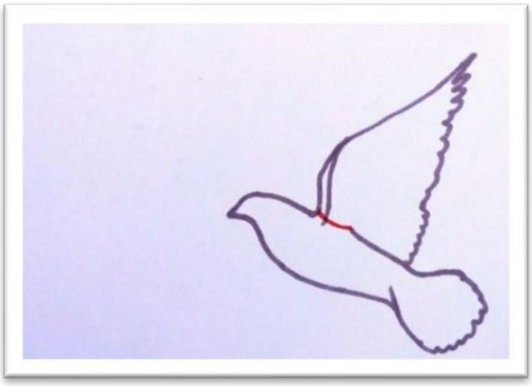

Fig. 1 b. Lateral view of the fitted harness.

The harness was designed to be lightweight and comfortable for the birds to wear for an extended period and, to minimise the risk of snagging and meet the conditions of ethical approval, did not project outside the natural feather contour of the bird. Based on previous designs, the wing loops of harness were constructed using soft, elastic nylon (Wangjiangda Elastic Cord for Masks 3 mm). Male brass spade connectors were used as the point of articulation (Agger brand, 2.8 mm) because they had a uniform, flat surface which could be glued, and had a central hole in the spade, through which a rubber band could be knotted to hold the harness together. The process of connecting the spade connectors to the wing loop cord involved knotting the end of the cord and inserting it into the crimp on the spade connector, which was subsequently crimped shut. The junctures of the spade connectors and wing loops were then covered with soft polyethylene tubing (OWIM GmbH & Co KG. Stuttgart, HRA 721742) to mitigate any abrasion caused by knots or metal edges. The flat ends of the spade connectors remained unwrapped, to facilitate the inclusion of the test material and expose it to the atmosphere *(Fig. 2)*.

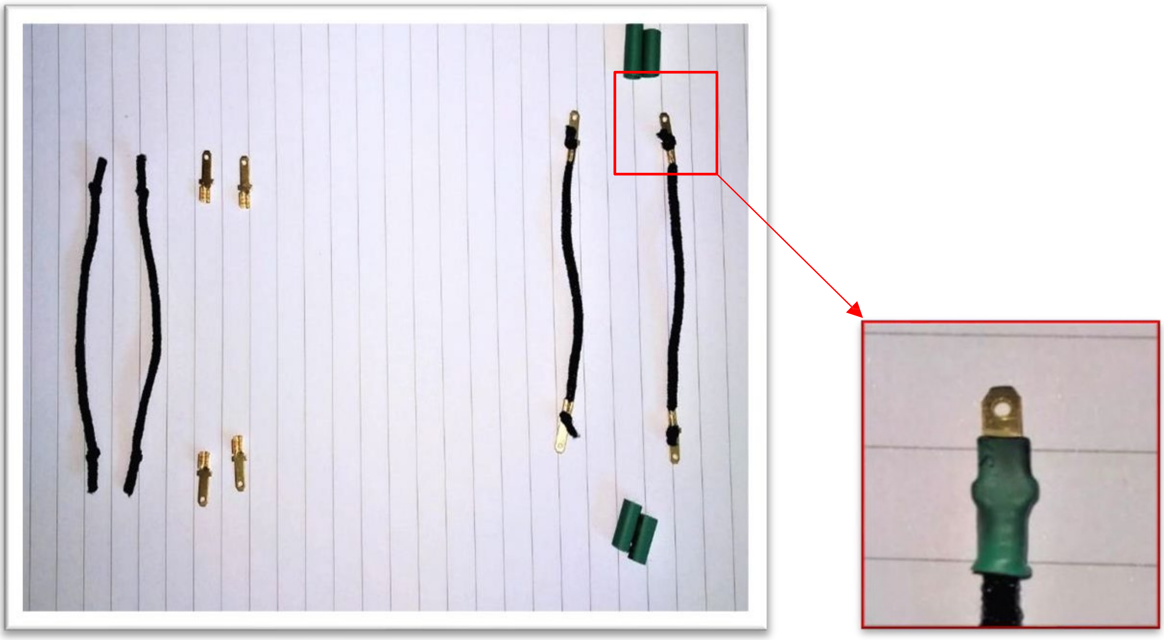

Fig. 2. Parts used in construction of the simple wing loop harness, showing detail of wrapped end.

Despite the variety of manufactured elastic bands, only three suitably sized types of bands with known composition could be easily sourced. This was because the elastic bands had to be narrow enough to thread through the spade connectors without overstretching or deforming, potentially weakening the elastomer (Mullins 1948). The bands also had to be sufficiently strong to be knotted successfully. The types tested were: Thermoplastic Polyurethane (*TPU - Cosy Companions*), Silicone (*Tigerbox*) and Natural Rubber (*Tigerbox*) which had their cross-sectional areas determined microscopically as 0.66 mm^2, 1.5 mm^2 and 1.69 mm^2 respectively using an S1 Micrometer scale of 10 mm in 0.1 mm divisions. A wide range of branded adhesives were also available. However, the majority had a similar chemical profile. Cyanoacrylates were discounted from the trial as their properties have been extensively monitored in biologging experiments using direct external mounting methods, and they have already been subject to similar research (Herring and Gawlik 2010). The following adhesives were trialled because of their different chemical profiles: Evo-stik Impact, a polychloroprene-based contact adhesive (Bostik 2015); UHU Universal, a polyacrylate (Bolton 2022), and Gorilla Glue Contact Clear, a silane (Gorilla 2022).

2.2. Rubber band breaking stress tests

Incorporating a rubber band into a harness as the weak link often requires it to be knotted. Knotting any material causes a significant reduction in strength, sometimes more than fifty percent of the unknotted breaking stress (Martin et al. 2015, Montgomery 1977). With any sharp bend of a knotted material, the outside of the bend, which is extended to the greatest degree, carries the majority of the load, and the inside of the bend will carry very little of the load, being compressed (Poier et al. 2014, Saitta et al. 1999, Zhang et al. 2019) (*Fig. 3*). A knot with multiple turns increases the strength of those forces (Turner 1996) but the tension at which the knot is tied is a significant factor in the failure of the material. It was therefore necessary to quantify the breaking stress of the rubber bands before an attempt at knotting was made.

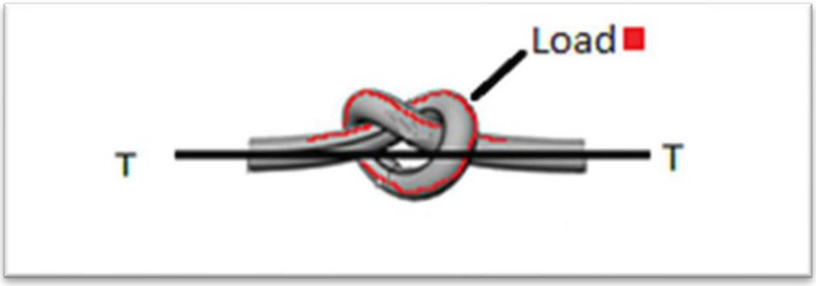

Fig. 3. Area of maximal load on a knot (T=tension applied)

Six randomly sampled rubber bands of each type were individually hung from a stand using a steel hook. A second steel hook was inserted through each band's loop, and incremental 10 g masses were carefully added, with a 5-second interval between each addition, until the stress led to rubber band failure.

The mean breaking stress of each type of unknotted rubber band was calculated and this served as a basis to estimate the force required for successful knotting without breakage. However, as there was no direct comparison, it was decided to start at fifty percent of the unknotted breaking stress mentioned previously (Martin et al. 2015, Montgomery 1977). Also, because the rubber bands would be incorporated into the harness, placement in the design needed to be considered. To accomplish this, bands were threaded through the eyelets of the spade connectors, using a needle threading tool, mating the surfaces of two plates together. Care was taken to only apply traction to a small, terminal section of the rubber bands to minimise stress before knotting.

A square knot was chosen because it was simple to tie in such a small rubber band, it lies reasonably flat, which would reduce chafing when incorporated into a harness, and has minimal throws. The first throw of the knot was loosely made, then, whilst holding one end of the elastic static, the other was clamped at the end of a Pesola 1000g spring balance and, using the balance as a dynamometer, pulled carefully until the calculated threshold tension was reached *(Fig. 4)*. Initially, 50% of the minimum unknotted breaking stress of each rubber type was tried because this was seen as a good starting point based on previous observations of rope (Martin et al. 2015), but the tension in the knots pulled the elastic material too tight, and 14 of the 18 test samples snapped before the second stage of the knot was tied, giving a failure rate of 78% overall. On the second attempt, using 25% of the lowest breaking stress, 10 bands snapped, giving a failure rate of 56%. Finally, only 10% of the minimum breaking stress was used, which was successful for all 18 bands, being (Newtons): TPU, 1.71; Silicone, 3.23; Natural Rubber, 3.61. When the tension was released, the friction in the knot held it in place for the second, locking throw, which was tied by hand and tightened, in the same way as the first throw, to maintain the original tension. The breaking stress of the knotted elastomers was then tested by adding 10 g masses until the elastic weak link failed.

Fig. 4. Tying knot to tension using Pesola scale as dynamometer.

2.3. Adhesive Shear strength tests

All the adhesives were specified as suitable for use on metal and so the same type of brass spade connectors, which were used for the rubber bands, were used as the adherends. The connectors were surface prepared, as per the manufacturers' recommendations. To achieve proper adhesion, the spade connectors were degreased using isopropyl alcohol swabs and abraded with 1200-grade abrasive paper to enhance mechanical bonding before gluing. A small paintbrush was used to apply an even layer of adhesive. The two prepared adherends were then overlapped at 180 degrees to form a single lap joint and were left to cure for the recommended period before testing for shear strength (*Fig. 5*).

Fig. 5. The prepared brass spade connectors

Once cured, the same shear strength testing method was applied. The bonded brass spade connectors were suspended from a metal stand, and 10-gram masses were added incrementally via a steel hook inserted through the crimp until bond failure occurred.

2.4. Survival Testing

The next stage was survival testing under load to quantify the length of time the rubber bands and adhesives would remain intact. These tests were performed in the open air to test natural weathering survival, and in a controlled temperature room without being subject to UV light. Each elastomer or adhesive was subject to loads of 10, 20, 60 and 80 grams, with five samples of each load, totaling 20 samples of each material. Two racks were constructed from timber and steel mesh with enough room to hold the samples without entanglement. The samples were suspended from small metal hooks in homogenous groups, for ease of identification. One rack was set up on 26/04/2022 on the roof near the pigeon loft at an altitude of 24 metres. It was situated in an alcove facing SSE, at coordinates 51°36'27.4"N 3°58'54.7"W, in an area that was shaded for several hours of the day and provided shelter from the prevailing SW wind *(Fig. 6)*. The amount of direct sunlight it received depended on the season. Initially, a Kestrel 5510 was used to log weather data, however unpredictable premature battery failure led to incomplete records. Consequently, the climate data from the nearest weather station, Mumbles Head, 2.7 miles South of the test site were requested from the Meteorological Office Archives and used for the analysis. To assess the natural decay progression due to weathering, the broken bands were examined through microscopy and photographed as the survival time extended.

A second rack was arranged in the same way and placed in a constant temperature room, with the controls set to 30 º C. Humidity could not be controlled in the room, however, previous monitoring showed minimal percentage humidity fluctuations. The temperature and humidity inside the CT room were monitored by a Kestrel D2 drop tag. In both cases, samples were observed daily before 9 am.

The survival time of the rubber bands was trialled on live birds by incorporation into a small wing loop harness. Due to time constraints, it was not feasible to include the adhesives in the live birds testing because even several months after the initial experimental set-up for weathering, the majority of adhesives had still not failed. Nonetheless, the gathered data remained pertinent and informative for the purpose of this investigation.

Fig. 6. Test rack for natural weathering showing suspended samples

Each bird was measured using a length of the stretch cord comfortably looped, from the centre point between its scapulae, around its wing and returning to the starting point. Two lengths of the cord were cut and had a small knot tied as close to the ends as possible. A spade connector was then crimped around the knotted end and covered in soft shrink tube to avoid causing any abrasions to the bird. The heat shrink was colour coded according to elastomer type for easy identification when a detached harness was recovered from the pigeon loft. The ends of the spade connectors were left free of shrink wrap so the elastomers could be threaded through. The spade connectors were overlapped in sequence 1 to 4, to balance the tension evenly across the birds' wings *(Fig. 7)* and joined together by threading the rubber bands through the holes in the plates. Finally, the knot was tied using the Pesola scale as a dynamometer.

Harnesses were fitted to the birds by putting a wing in one loop, then stretching the harness over the other wing, which positioned the weak link between the scapulae. The cord was elastic enough to enable this without adjustment. The birds preened the harnesses under the feathers over the following 24 hours and little could be seen outside the natural contour of the feathers. Ten birds were used in the harness tests and each bird trialled all three types of rubber band. Birds were examined daily after having a harness fitted, to check for abrasions or entrapment issues.

Fig. 7. Assembly of the harness, showing the order in which the ends were connected to balance tension.

When a harness failed, bird ID, type of elastomer and days lifespan were noted. A new harness with a different elastomer was then fitted to the same bird, until all ten birds had trialled all three elastomers.

The pigeons used in the study were tippler, tumbler and roller varieties of fancy pigeons that varied in colour and mass. They were housed in a timber pigeon loft at Swansea University with access to an outdoor aviary. They were fed a mixed grain, seed and legume diet and were released to free fly several times a week until Avian Influenza restrictions came into force in December 2022. All birds were measured and weighed at the start and end of the study and body mass was monitored weekly as part of routine husbandry procedures. Skin temperatures were taken from different areas of the pigeons on two days during the study, with a small, flexible temperature probe attached to a pre calibrated AstroAI DT132A Multimeter and feather colour was noted as dark or light. (*S. Table 1*). Ethical permissions for all live bird experiments were granted by Swansea University Animal Welfare and Ethical Review Body (permit 060722/482).

2.5. Data analysis

In order to assess potential significant variations in breaking stress across the three distinct types of unknotted rubber bands, a one-way analysis of variance (ANOVA) was conducted. The data satisfied the assumptions required for ANOVA analysis and subsequently, a post-hoc Tukey's honestly significant difference (HSD) test was performed to compare the mean breaking stress of each pair of rubber bands individually.

An ANOVA was also performed on the breaking stress data for the knotted rubber bands, but the data failed the Levene’s test of homogeneity and the Shapiro-Wilk normality test. An outlier was removed from the data set which normalised the data distribution, but the data still failed the Levene’s test of error variances. A Kruskal-Wallis test of group medians was therefore performed to compare the breaking stress of the knotted rubber bands. This test does not require the assumption of normally distributed data, and it is suitable for comparing more than two groups. Dunn’s test was used for post hoc comparisons. Shear strength of the adhesives was analysed with another ANOVA and Tukey’s HSD was used for post hoc testing. All ANOVAs and associated tests were run using SPSS (IBM v. 28.0.1.1(15)).

The survival data for natural weathering and CT room samples under load were modelled in R using RStudio (2022.12.0/353) by running Generalized Linear Models (GLM) to include the multiple predictors of rubber or adhesive type, load, temperature and humidity.

For the CT room data, one outlier was removed from the rubber band data set, because the band failed significantly before the others of the same type and load, and another was removed due to the significantly longer survival time, which was around twice that of other bands of the same type and load, which skewed the data. No data points were removed from any of the natural weathering tests or the adhesive data.

The mean temperature and humidity for each groups’ survival time was calculated and used for the model, i.e. mean temperature for all 10 gram, 20 gram etc. Post hoc comparisons were made using the Emmeans package with Tukey's adjustment. The live bird harness survival data were also modelled using a GLM with rubber type and feather colour as predictors. Temperature was not used as a predictor in the GLM due to the narrow temperature range and there was no reliable method to test sub-feather humidity. The Emmeans package with Tukey's adjustment was used to identify any significant comparisons. Goodness of fit for all five GLM models were calculated using the McFadden pseudo R^2 (McFadden 1973), with values between 0.2 and 0.4 showing satisfactory fit.

3.0. <u>Results</u>

3.1. Rubber band breaking stress

When rubber bands were unknotted, the breaking stress varied with band type (TPU, Silicone and Natural Rubber) (ANOVA, $F_{2, 15} = 3502.305$, $p < .001$, $\eta^2 = 0.998$), with Natural Rubber having the highest breaking strain and TPU the lowest. Tukey's HSD post hoc testing indicated that the mean breaking stresses of each band type were significantly different (mean breaking forces; TPU=17.2 N, Silicone =32.6 N and Natural Rubber 36.6 N, p<0.001).

There was also a significant difference between the median ranks of the three rubber band types when they were knotted (Kruskal-Wallis test, H (2) = 10.260, p = 0.006). Natural rubber had the highest breaking strain and TPU the lowest, however, post hoc testing revealed that there were only significant differences between TPU and Natural Rubber (H (2) = -9.500, p = 0.002), and between Silicone and Natural Rubber (H (2) = -7.750, p = 0.012). The test statistic was automatically adjusted for ties.

Knotting the bands resulted in a substantial reduction in the mean breaking stress irrespective of band type, with TPU, Silicone, and Natural Rubber bands showing decreases of -66 %, -81%, and -67%, respectively (*Fig. 8*) (knotted mean breaking stresses; TPU 5.80 N, Silicone 6.17 N, Natural Rubber 12.27 N). Bands were knotted in all subsequent analyses as part of the weathering tests and when integrated into a wing loop harness.

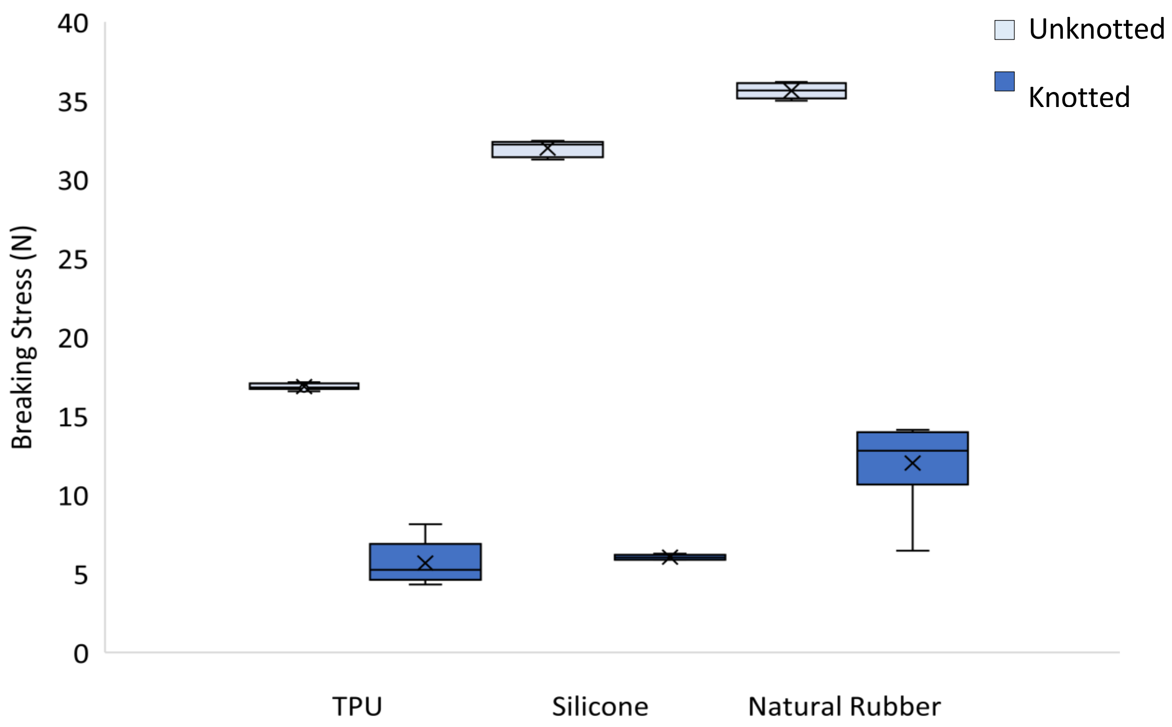

Fig 8. Comparative breaking stress of knotted versus unknotted elastic bands

3.2. Survival analysis -Survival times across treatments

Among the three types of bands incorporated into harnesses and tested on live birds, TPU had the lowest median survival times for all three rubber types. The naturally weathered bands had slightly longer median survival times compared to the live bird test and the bands tested in the CT room had the longest median survival times, significantly surpassing the live bird test, especially for the TPU, and showing greater range of survival overall *(Fig 9).*

Interestingly, the TPU band in both the natural weathering and live bird tests had a very narrow range and similar mean survival time. A narrow range was also shown in the Silicone survival time for live bird testing, but this range was extended in the naturally weathered experiment. Natural Rubber exhibited similar range and survival time for both live bird tests and natural weathering.

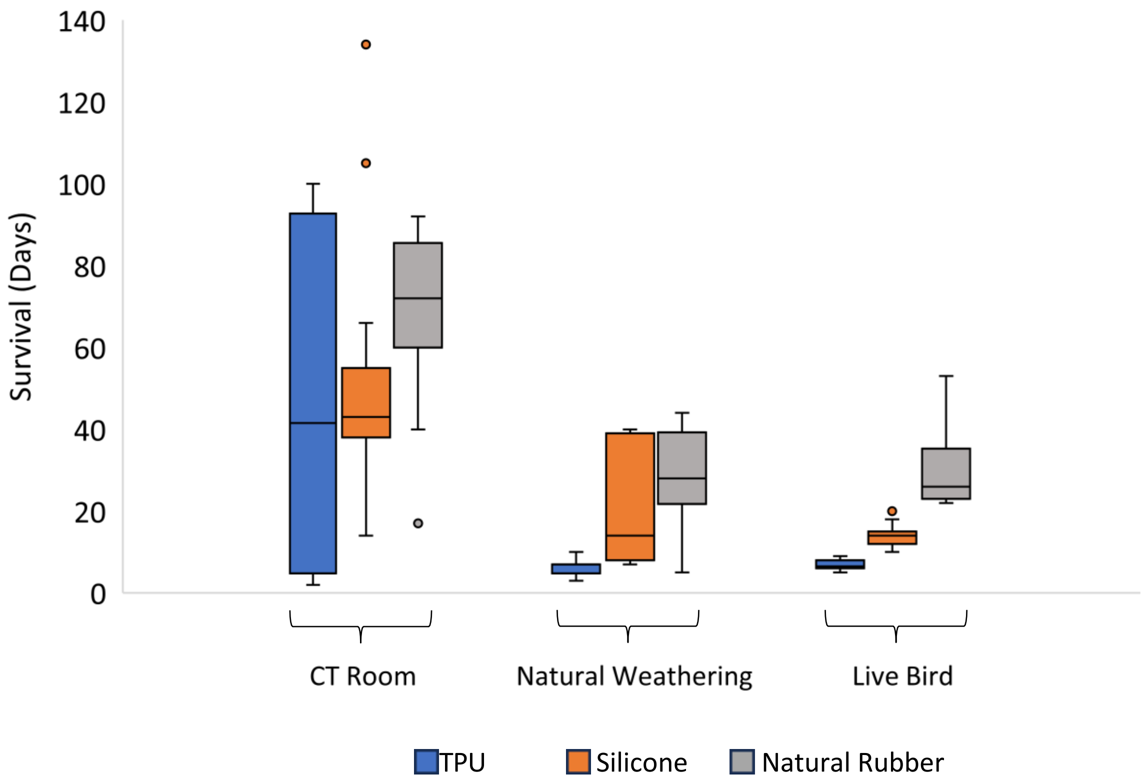

Fig. 9. Comparison of rubber band type survival under contrasting conditions. Note that bands kept in the CT-room and those subjected to natural weathering were tested with a range of loads, whereas those incorporated in harnesses on live birds were attached using the standard tension for that particular rubber type which was determined in breaking strain tests.

3.3. Survival analysis of rubber bands subject to natural weathering

A Generalized Linear Model (GLM) was used to predict how rubber band survival time varied according to rubber type, temperature, humidity and load. The model had a reasonable fit (McFadden Ps. R^2 0.67), although the high McFadden score could indicate a degree of overfitting. Temperature had a significant positive effect on the survival time (estimate = 0.778, SE = 0.201, t_{52} = 38.635, p <0.001) such that, for each 1 °C increase in temperature, the survival time increased by 2.2 days. Humidity also had a positive effect on survival time (estimate = 0.024, SE = 0.004, t_{52} = 6.098, p < 0.001), with each 1% increase in humidity resulting in an increased survival time of 1.0 day.

Rubber band types did not differ in survival time, however their response to load varied. TPU and Silicone showed no effect of load, but Natural Rubber demonstrated a significant interaction with it (estimate = -0.002, SE = 0.001, t_{52} = -2.705, p = 0.009). Median survival times were TPU = 7 days, Silicone = 10.5 days, and Natural Rubber = 29.5 days (*Fig. 10*).

3.4. Survival analysis of rubber bands in CT room

A GLM of the survival time of rubber bands in the CT room revealed that, similar to the bands tested outdoors, temperature had a significant positive effect on survival time (estimate = 0.704, SE = 0.252, t_{48} = 2.795, p = 0.007) with each 1 °C increase in temperature being associated with an increased survival time of 2.0 days. Humidity had a significant negative effect on survival time (estimate = -0.455, SE = 0.046, t_{48} = -9.968, p < 0.001) with each 1% increase in humidity resulting in a decrease in survival time of 0.63 days. There were no significant differences in survival time between the rubber bands, but the analysis showed that when subject to increasing load, the survival time of the Silicone band was significantly negatively affected (estimate = -0.001, SE = 0.002, t_{48} = -4.733, p < 0.001). The model overall had a good model fit (McFadden Ps. R^2 0.31).

The Tukey HSD post hoc comparisons revealed that, when subjected to the reference load of 43.2 g, the survival time of TPU was statistically different to Silicone (estimate = 0.452, SE = 0.168, t_{48} = 2.687, p = 0.026). However, there were no significant differences in survival between TPU and Natural Rubber (estimate = 0.433, SE = 0.183, t = $_{48}$ 2.359, p = 0.057), or between Silicone and Natural Rubber (estimate = -0.019, SE = 0.092, t_{48} = -0.211, p = 0.976). Median survival times across all load ranges were TPU = 41 days, Silicone = 43 days, and Natural Rubber = 72 days (*Fig. 10*). While the post hoc tests did not yield significant differences between materials when subjected to the reference load of 43.2 g, the descriptive statistics, specifically the median survival times, revealed notable variations.

The premise of the Controlled Temperature Room (CT Room) was to maintain a constant temperature, providing a controlled environment for experimentation. However, due to unanticipated technical complications and a partial failure in the temperature control system, the room experienced some variation in temperature during trials. The TPU samples experienced a temperature range of 0.49 °C (31.60 – 32.90 °C) and a humidity range of 8.43 % (31.29 – 39.72 %); Silicone bands experienced a temperature range of 0.45°C (31.60 – 32.05 °C) and a humidity range of 2.75% (31.23 – 33.98 %) and the Natural Rubber bands a temperature range of 0.46 °C (31.63 – 32.09 °C) and a humidity range of 2.3% (31.24 – 33.54 %). The TPU rubber experienced greater fluctuations in humidity than the Silicone and Natural rubber bands.

The rubber bands subjected to natural weathering experienced more varied environmental conditions, including cooler temperatures, with the TPU samples in this scenario having a wider temperature range of 0.7 °C (10.31 - 11.01 °C), compared to 0.49 °C in the CT room. Similarly, Silicone and Natural Rubber samples also showed wider temperature ranges in the outdoor setting (Silicone, 2.49 °C, range from 10.31 to 12.80 °C, Natural Rubber range of 2.22 °C, from 10.76 to 12.98 °C). The humidity ranges were significantly higher for all rubber types when subjected to natural weathering, with TPU exhibiting the highest range of 14.36% (65.20 - 79.56 %), followed by Silicone with 10.47% (71.99 – 82.46 %), and Natural Rubber with 6.65% (75.81 – 82.46 %).

3.5. Survival analysis of rubber bands incorporated into harnesses for live bird testing

When rubber bands were incorporated into harnesses and deployed on pigeons, the bands failed between 5 and 67 days. The median survival times were TPU = 6.5 days, Silicone = 14 days, and Natural Rubber = 26 days (n=10 bands per group, *Fig. 9*). A GLM of the band survival time revealed significant variation in survival with rubber band type (estimate 0.702, SE 0.061, $t_{26} = 11.480$, $p<0.001$) but not feather colour ($p=0.061$). Based on the Tukey post hoc analysis, Natural Rubber had a higher survival time than TPU (estimate = -1.514, SE = 0.116, t_{26} = -13.089, $p < 0.0001$) and Silicone (estimate = -0.831, SE = 0.121, t_{26} = -6.853, $p < 0.000$) and Silicone also had a higher survival time compared to TPU (estimate = -0.683, SE = 0.121, t_{26} = -5.627, $p < 0.0001$). The GLM had a good model fit (McFadden Ps. R^2 0.31).

3.6. Adhesive shear strength

The shear strength, tested by exposing bonds to increasing loads, differed between the adhesive types (Evo-Stik Impact, UHU Universal and Gorilla Glue Contact Clear) (ANOVA, $F_{2, 15}$ = 38.593, $p < 0.001$, $\eta^2 = 0.837$). Tukey's HSD post hoc testing indicated that the mean shear strength of Evostik impact was significantly higher than UHU Universal ($p < 0.001$) and Gorilla Clear Contact (p = 0 .043), and Gorilla Clear Contact was higher than UHU ($p <0.001$). There was no statistical difference between Evo-Stik and Gorilla Clear Contact (*Fig. 11*). The mean shear strengths were Evo-Stik Impact = 30.2 N, UHU Universal = 7.1 N and Gorilla Glue Contact Clear = 23.0 N.

3.7. Survival analysis of adhesives subject to natural weathering

The adhesives kept in outdoor conditions had markedly longer survival times than the rubber bands, with median survival times of 114 days for Evo-Stik Impact, 207 days for UHU Universal and >365 days for Gorilla Glue Contact Clear (*Fig.12*). A GLM of the adhesive survival times revealed that temperature had no significant effect on the survival time of any adhesive type (estimate = 0.145e -01, SE = 7.225e-02, t_{50} = 2.000, p =0.050). However, humidity had a significant positive effect on the survival time (estimate = 0.024, SE = 0.004, t

$_{50}$ = 6.098, $p < 0.001$), with each 1% increase in humidity increasing the survival time by 1.3 days. There were no significant differences in survival time between Evo-Stik Impact and UHU Universal (estimate = 1.036e-01, SE = 1.077e-01, t_{50} = 0.962, p = 0.341), however, Gorilla Glue Contact Clear had a longer survival time compared to Evo-Stik Impact (estimate = 3.861e-01, SE = 1.275e-01, t_{50} = 3.028, p = 0.004). The effect of load was only statistically significant for Evostik Impact (estimate = -4.076e-03, SE = 1.370e-03, t_{50} = -2.975, p = 0.005). Overall, the model provided a moderate fit to the data (McFadden Ps. R^2 0.19).

The Tukey HSD post hoc comparisons revealed that all adhesives had distinctly different survival times when subjected to the reference load of 43.21 g., Evo-Stik Impact demonstrated a lower survival time when compared to UHU Universal (estimate = -0.246, SE = 0.071, t_{50} = -3.466, p = 0.003) and Gorilla Glue Contact Clear (estimate = -0.554, SE = 0.096, t_{50} = -5.765, $p < 0.0001$), and there was a significant difference in survival time between UHU Universal and Gorilla Glue Contact Clear adhesive (estimate = -0.308, SE = 0.085, t_{50} = -3.617, p = 0.002)

3.8. Survival analysis of adhesives in Controlled Temperature (CT) room

The survival times of the adhesives were broadly similar when they were kept in controlled conditions, with median survival times of 86 days for Evo-Stik Impact, 365 days for UHU Universal (which was notably longer than when this adhesive was kept outside), and > 365 days for Gorilla Glue Contact Clear (*Fig. 12*).

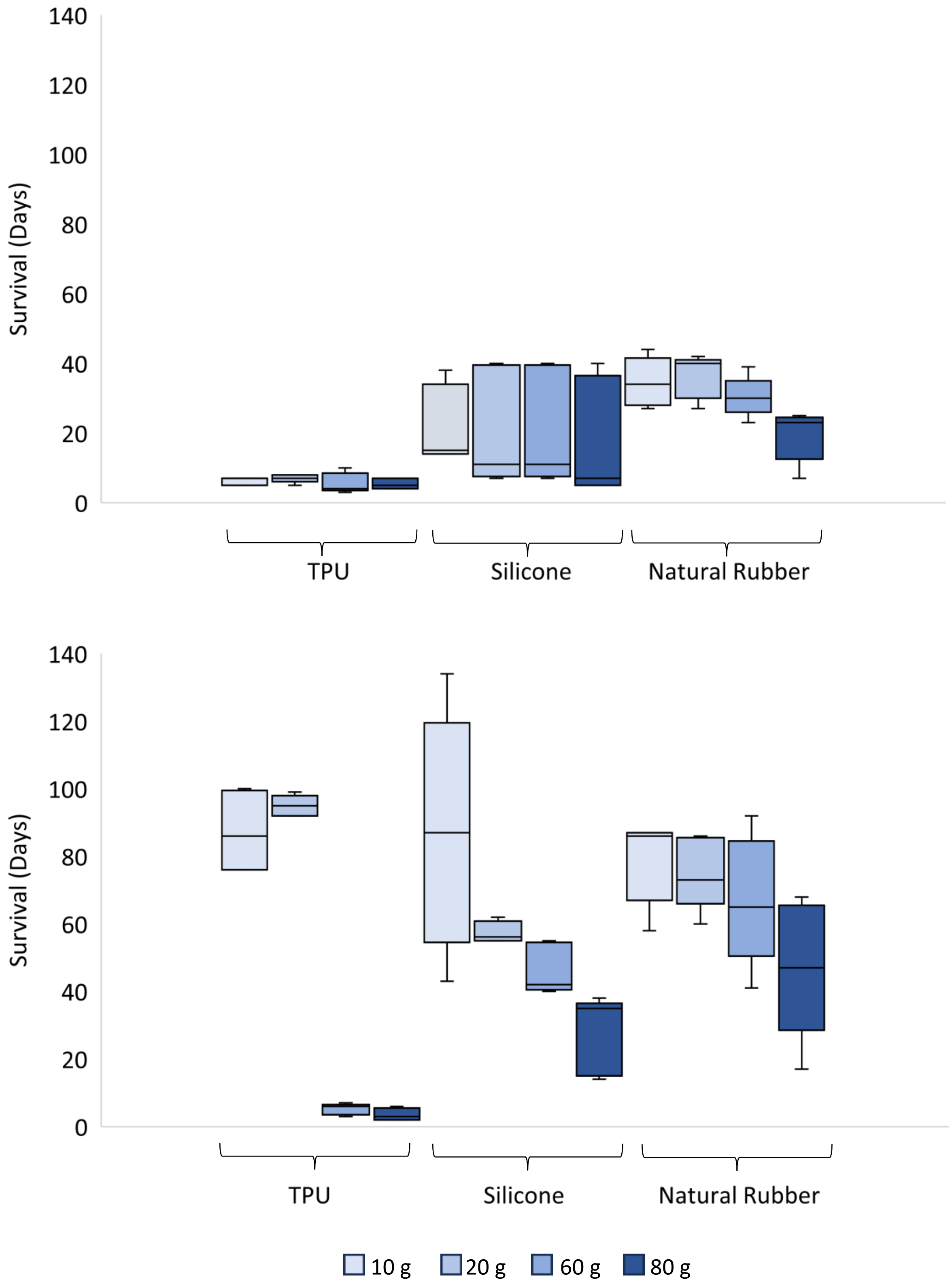

Fig 10. Rubber band survival time by load (inclusive median) when subjected to natural weathering (upper panel) and in the CT room (lower panel).

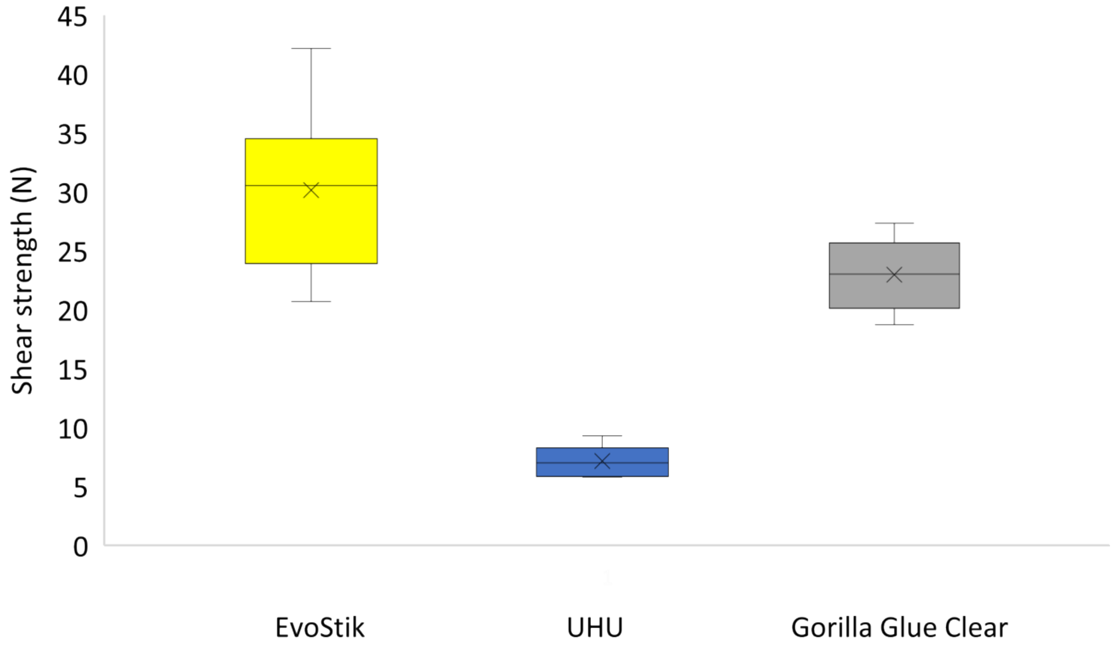

Fig. 11. Comparative shear strength of adhesives

In contrast to the adhesives kept outdoors, the survival times of the adhesives kept in the CT room did vary with temperature. In fact, the GLM showed that temperature had a significant negative effect on the survival time (estimate = -764e -01, SE = 5.805e -02, t_{54} = -13.164, p <0.000), with a drop in survival of 0.56 days for every 1 °C increase in temperature. Humidity had no significant effect on the survival time in this experiment (estimate = 5.129e -02, SE = 2.673e -02, t_{54} = 1.919, $p < 0.000$). Similar to the outdoor survival times, adhesives differed in their survival time according to the type, with significant differences in survival time between Evo-Stik Impact, UHU Universal (estimate = 2.091e-01, SE = 6.230e -02, t_{54} = 3.403, p = 0.002) and Gorilla Glue Contact Clear (estimate = 2.120e-01, SE = 1.275e-01, t_{50} = 3.028, p = 0.001). However, the effect of load in the model was not significant for any adhesive (p>0.05. The model provided a good fit to the data (McFadden Ps. R^2 0.33).

The Tukey HSD post hoc comparisons revealed that all adhesives had different survival times when subjected to the reference load of 43.21 g., with load having a statistically significant negative effect on the survival time of Evo-Stik Impact when compared to UHU Universal (estimate = -0.175, SE = 0.043, t_{54} = -4.119, p = 0.000) and Gorilla Glue Contact Clear (estimate = -0.193, SE = 0.054, t_{54} = -3.606, $p < 0.002$). However, no significant difference between UHU Universal and Gorilla Glue Contact Clear adhesive was demonstrated (estimate = -0.186, SE = 0.031, t_{54} = -0.607, p = 0.817).

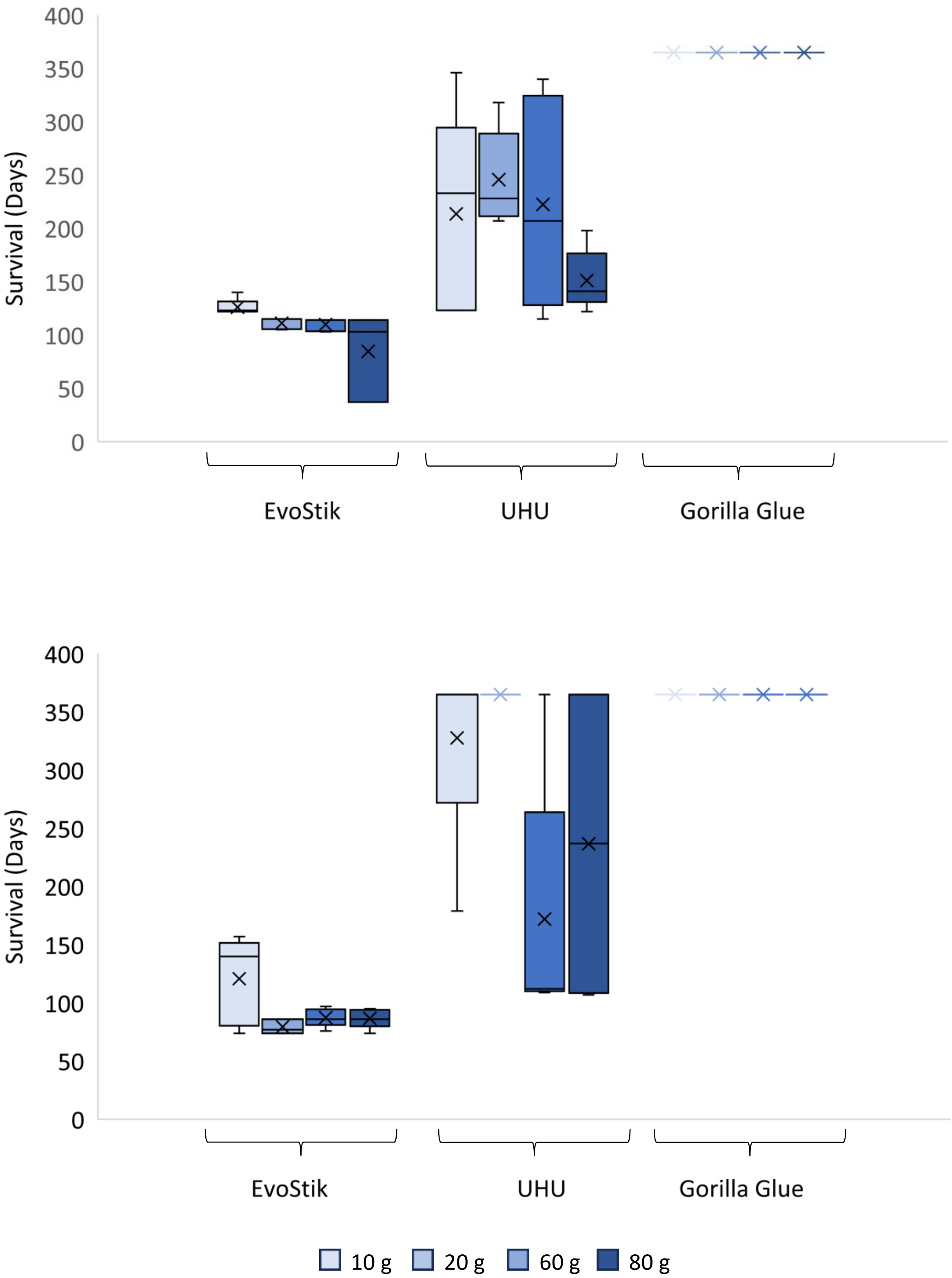

Fig. 12. Comparison of adhesive survival under load in contrasting conditions showing Natural Weathering (top panel) and CT room (bottom panel).

3.9. Effects of natural weathering and CT room exposure on rubber bands and adhesives.

Rubber bands were inspected under a microscope across the range of failure times to provide insight into the cause of failure. The different rubber bands exhibited distinct patterns of degradation. TPU and Silicone showed surface powdering and developed stress-induced striations and deep cracks as part of the embrittlement process. Each new TPU rubber band showed minimal signs of wear on the first day. The TPU band that broke on day 3 showed little deformation and only slight surface flakes in a low-stress region away from the knot. By day 4, a broken band exhibited surface powdering, with stray debris adhering to the band's surface. On day 7, deep striations were seen near the knot, indicating plastic deformation caused by the breakdown of the material's bond. The band that failed on day 10 pitted surface indicating particle loss, with a stress-whitened area adjacent to the break (*Fig 13*).

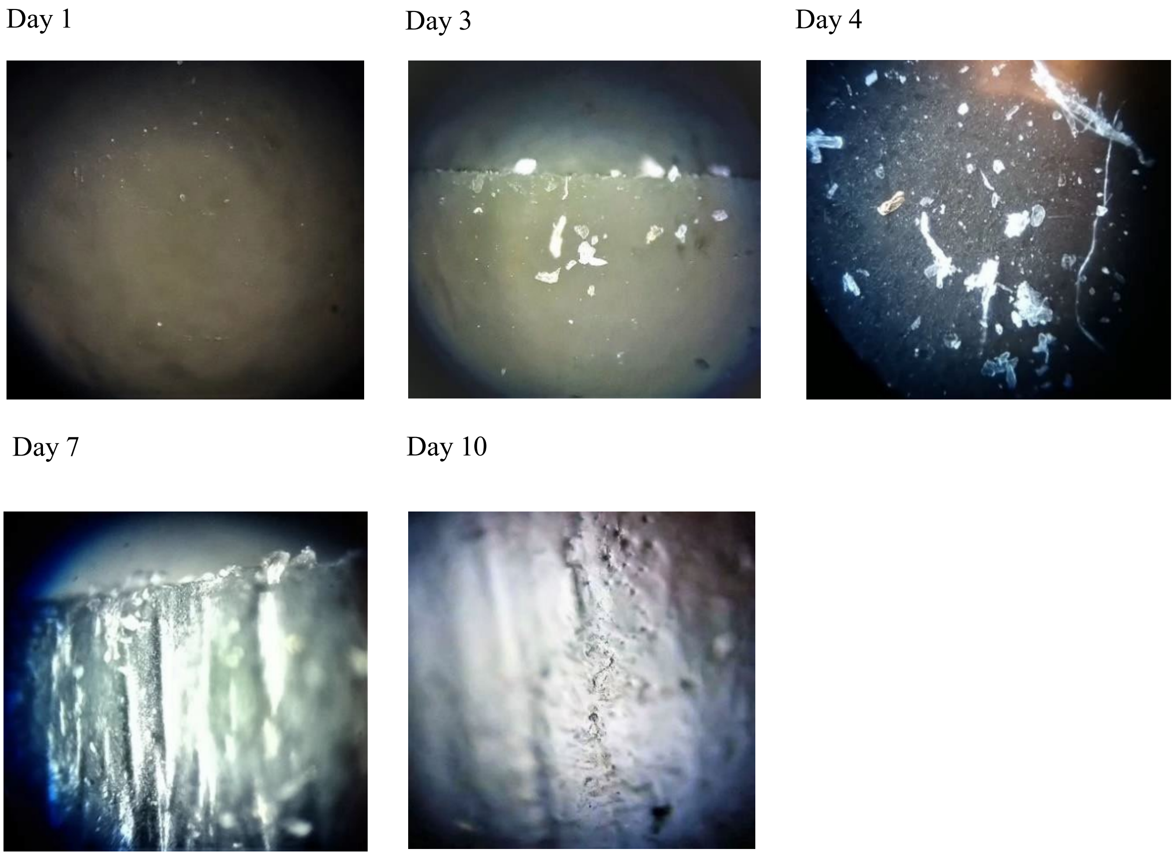

Fig 13. Natural weathering of TPU bands over time. Viewed at 100 X magnification.

The Silicone band failed on day 5 had slight deformation and surface powdering, in a region far from the knotted point of breakage. On day 12 the broken bands began to show stress-induced striations, providing a clear indicator of increasing material fatigue. By day 20 there were conspicuous deep cracks, particularly near the knot, where all the bands had snapped. Finally, on day 40, the last remaining band exhibited marked pitting along with a prominent stress-whitened area adjacent to the break (*Fig. 14*).

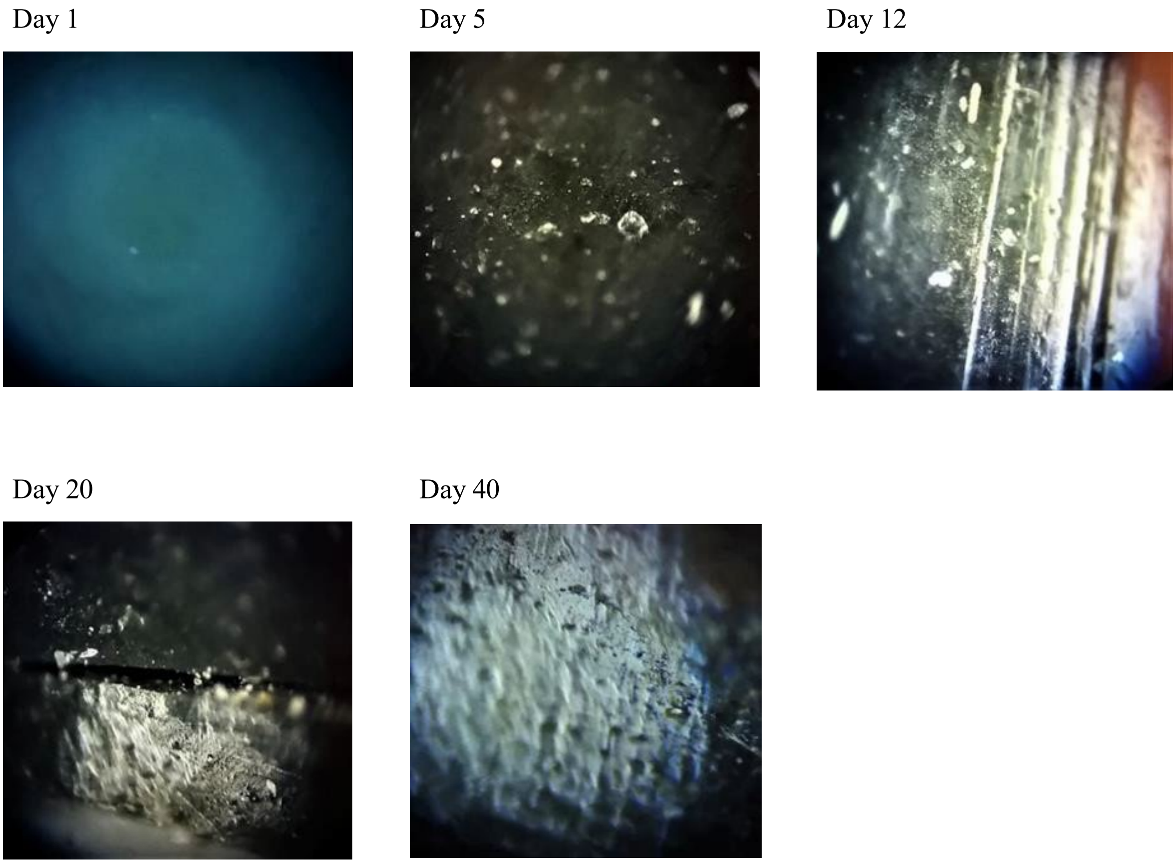

Fig. 14. Natural weathering of Silicone bands over time. Viewed at 100 X magnification.

The Natural Rubber showed a different pattern of degradation. The band that failed on day 7, had a melted and gummy appearance. On day 23, stray debris began to adhere to the gummy surface. By day 35, the surface of a broken band near the tension area appeared deeply wrinkled and puckered. Finally, on day 44, a liquid-like, gummy, and stretched area was noted next to the point of breakage (*Fig. 15*).

The degradation process appeared to be different for bands in the CT room. All bands had lost a significant amount of flexibility and appeared much drier than their naturally weathered counterparts. The TPU bands in the CT room degraded into a weak, dry and powdery state. The Silicone samples appeared quite desiccated, and the last of the Natural Rubber samples to fail had become somewhat dry.

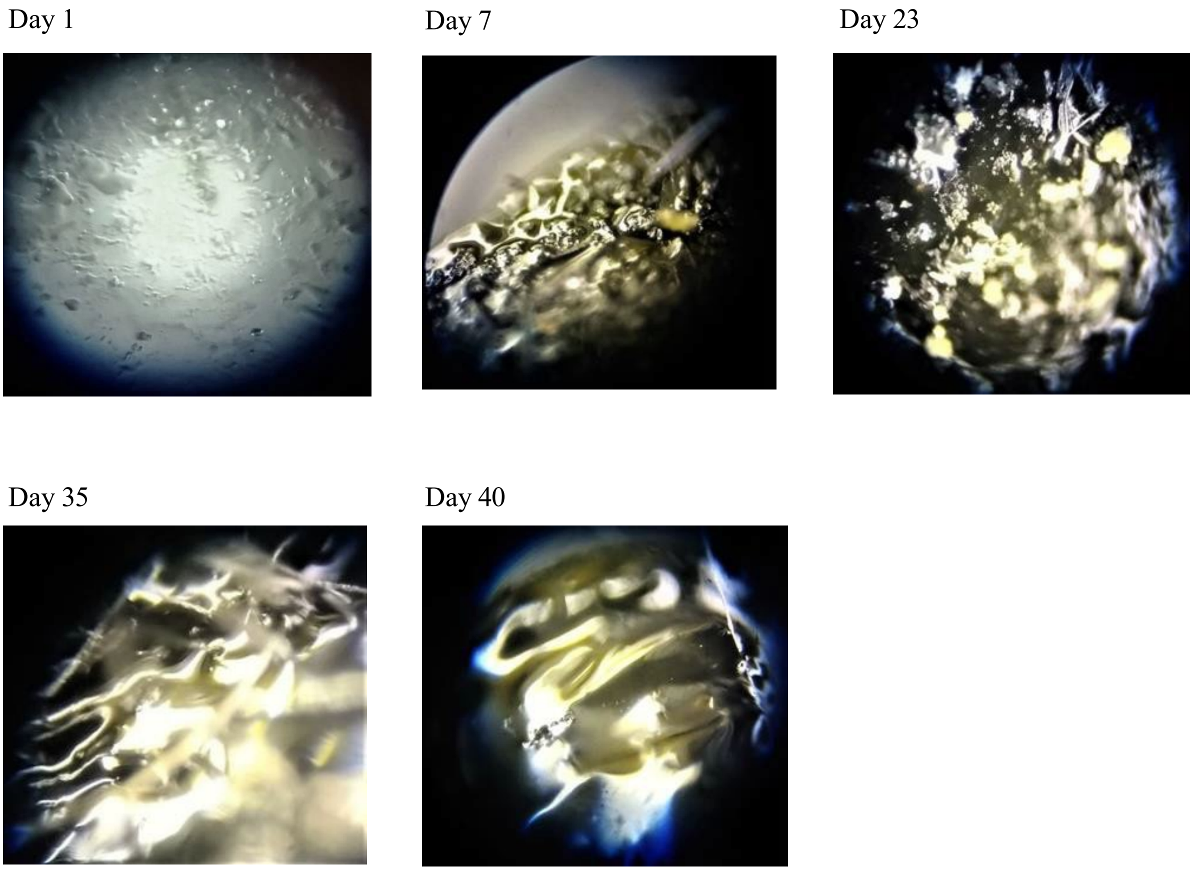

Fig. 15. Natural weathering of Natural Rubber bands over time. Viewed at 100 X magnification

The adhesive bonds appeared to vary with adhesive type and environmental conditions. None of the Gorilla Glue samples failed. The failed samples of naturally weathered Evo-stik retained some flexibility but there were blistered areas that had pulled away from the adherend. The Evo-Stik samples from the CT room had a few similar bubbles but the adhesive residue appeared flaky and dry. Samples of naturally weathered UHU appeared crazed and brittle and the adhesive had largely come away from the substrate in flaky sheets. The UHU in the CT room did not show the crazing of the naturally weathered samples, but it flaked easily. Both adhesives seemed to have been desiccated by the low humidity in the CT room.

4.0. Discussions

Multiple experiments were conducted to evaluate the suitability and survival times of three types of rubber bands, which could be considered as potential drop-off mechanisms when incorporated into the design of a bird harness. The rubber bands were subjected to tests measuring their breaking stress and endurance under varying conditions, including live bird trials. However, only the shear strength and survivability experiments were performed on the adhesives due to the extended and sometimes unpredictable survival times. The mean breaking stress and sheer strengths of the weak links in this study varied substantially from ~ 7 to 31 N for adhesives and 6 to 35 N for rubber bands. These break points are, of course, relative to the cross-sectional areas of the rubber bands and the surface area and adherend material for the adhesives, factors that also determined the survival times of the rubber bands and adhesives, which ranged from 3 to 44 days and 3 to >365 days respectively. Understanding how six different rubber bands/adhesives were affected by environmental conditions (temperature, humidity), load, and the interactions between them, became complex. Nonetheless, several materials were identified as inexpensive candidates for use as weak links.

4.1. Breaking stress and shear strength

Any release mechanism must be able to withstand the stresses of routine movements, such as forces exerted by the bird in flight, its attempts to remove the harness, and potential interactions with both conspecifics or the environment. The single most important determinant of breaking strain in rubber bands was whether or not bands were knotted, with knotting leading to a three to six-fold reduction in strength, depending on band type. The weakening of elastomers and other materials by knotting has been well documented (Poier et al. 2014, Saitta et al. 1999, Zhang et al. 2019) and is due to the deformation of the polymer chains at the knot. Consequently, bands are more likely to fail with increasing knot complexity and when tensile force is applied. This is a key consideration of how a rubber band should be incorporated into the harness. These properties could be manipulated by researchers, for instance, incorporating single, or complex knots with multiple throws would weaken the material and lead to a quicker drop-off.

Understanding the minimum breaking strain required for a given system is not straightforward as this will likely vary with a bird's behaviour, strength and lifestyle (which are likely inter-related). The forces that birds may exert by pulling on harnesses or weak links can be evaluated using force sensors (Carril et al. 2021). This was trialled in this study by offering pigeons a maple pea attached to a digital dynamometer, which could measure down to 0.5 N. Normally, pigeons would readily peck at a pea, but when they identified resistance from the strain gauge, they simply dropped the pea and ignored it or only tentatively explored it before rejecting it. This demonstrates the difficulties of quantifying how birds will interact with harnesses or weak links prior to developing such systems. Nonetheless, it did suggest that pigeons were unlikely to pull at the weak link with substantial force.

Bite force is also relevant when designing weak links and there are some published data on the bite force birds can produce. For example, the Sharp-shinned Hawk (*Accipiter striatus*) and Monk Parakeet (*Myiopsitta monachus*) have bite forces of 2.7 and 16.7 Newtons respectively (Carril et al. 2015). *Psittacines* often have a relatively high cranial mass, giving them greater bite force than passerines of similar mass. Such considerations are relevant if weak links are encased in hard materials for their protection.

4.2. Rubber bands

4.2.1. Overall performance and interactions of environmental stressors

This study highlights the importance of the rubber material on the effectiveness as a potential weak link. The Natural Rubber bands had the largest cross section, highest breaking stress and lasted the longest in all tests, suggesting that this material might be a more robust choice for attaching biologgers to birds if a longer duration is needed (within a range of 1-2 months).

Breaking stress alone is not necessarily a straightforward predictor of durability, as while Natural Rubber and Silicone had a similar breaking stress when tested at room temperatures, the performance of these materials differed markedly between the experimental scenarios. Survival times were therefore influenced by complex interactions between environmental parameters, band type and load. While the effect of temperature was consistent between experimental scenarios (with survival increasing with increasing temperatures), the effect of humidity and load varied with context and band type. The influence and interactions between environmental parameters are discussed in detail in the next section.

The predictability of survival times is another important consideration for the design of weak links. Interestingly, the range of survival times was narrowest for all three band types when they were tested on the live birds. The near constant temperature, warm, and relatively humid conditions in a sub-plumage environment may therefore allow for greater predictability of failure. Indeed, if weak links are preened under the feathers, then the band material, and how it is incorporated into the harness, are likely to be the most important determinants of survival time (as was found in this study). While Natural Rubber lasted the longest in live-bird trials, it was also the most variable in this treatment, in terms of survival days. Both TPU and Silicone had highly conserved failure times in the live bird trials. TPU also had highly conserved failure times in the natural weathering trials, but its performance was extremely variable in the CT room, making it inherently unsuitable as a weak link due to its unpredictability.

4.2.2. Rubber bands; effect of temperature and humidity

Temperature had the most consistent effect on band survival across all experimental scenarios, with survival time increasing with temperature in natural weathering and CT room trials. Consequently, if a band is groomed under the feathers, this should enhance survival times compared to results from room temperatures (all other factors being equal). This follows because temperatures are relatively high under the feathers. For instance, the median interscapular sub-plumage temperatures of birds in this study was 36 °C, when birds were at rest (range ±3 °C, at an air temperature of 20 °C and relative humidity of 52 %, *Table S.1*). This is over five degrees higher than the maximum temperature in the CT room. There were slight variations in temperatures across the body, with this area being the coolest measured in all ten birds. While the performance of elastomers declines at high temperatures, which is determined by type (e.g. Natural Rubber starts to lose cohesion at around 40 °C), bands are unlikely to be exposed to this range of temperatures while on birds, particularly if they are groomed under the feathers.

The way that the bands responded to temperature varied with band type. In the CT room TPU appeared to show a non-linear relationship with load, such that the survival time appeared to change abruptly above a threshold when bands were subject to temperatures of >30 °C , which may indicate a critical threshold temperature beyond which the material's mechanical behavior undergoes a significant change. Elastomers often undergo changes in their mechanical properties based on temperature fluctuations and, at higher temperatures, the molecular structure of many elastomers becomes more flexible, allowing for increased elasticity and deformation resistance (Ingmanson and Kemp 1938, Sakulkaew et al. 2013, Schieppati et al. 2018, Young and Danik 1994), leading to reduced resilience and accelerated degradation. In the context of the TPU survival under varying loads, the observed threshold effect noted in the CT room could be attributed to a temperature-induced shift in the material's mechanical behaviour. At around 30 °C, this type of TPU band may reach a critical temperature where its molecular structure undergoes a change, making it more vulnerable to mechanical stress. This vulnerability could manifest as a threshold weight beyond which the material experiences rapid failure. Such an effect was not observed in the naturally weathered samples which were subject to much lower temperatures. The more gradual, almost linear relationship seen in other elastomers implies a smoother transition in material behaviour with increasing temperature. Understanding more about the molecular and structural aspects of these elastomers could provide insights into why their longevity extends proportionally with higher temperatures and varying loads, but such research was beyond the scope of this study.

Humidity had a complex effect on survival, increasing it in natural weathering conditions, but decreasing it in the CT room. The effect of humidity may therefore depend on other factors, such as temperature variability and band type.

Silicone is hydrophobic (water repellent), making it relatively insensitive to higher humidity levels. However, as temperature increases and decreases, hygroscopicity alters and even small fluctuations in humidity can have a more pronounced effect on the material (Guan et al. 2012). When tensile stress is applied, such as the knotted area, increased localized stress concentrations within the material, make it more susceptible to failure. This effect may be more pronounced with the small, thin bands used in these experiments.

Natural Rubber, although hygroscopic (water absorbing), has been shown to retain its physical strength when waterlogged (Le Gac et al. 2015), which may explain the relatively longer survival time under the natural weathering conditions, despite damage from processes such as ozone cracking. However, it can desiccate in arid climates, such as in the CT room.

TPU is also hygroscopic, but repeated wetting and drying is known to significantly weaken the material (Boubakri et al. 2010). This could account for the negative effect of humidity for samples in the CT room and the short lifespan both on the bird and in the naturally weathered samples. Indeed, there seemed to be an increase in breakages when bands kept outside experienced periods of high humidity followed by drying, sometimes with several bands breaking on the same day.

There was no way of testing the sub-plumage humidity with any accuracy and it was not included in the model, but previous research on mallards (*Anas platyrhynchos*) has shown that humidity levels are 1.8 – 3.5 times greater in the sub-plumage microclimate, depending on the anatomical area, and the centre back (where tags typically sit) was the area of lowest humidity in one study (Coughlan et al. 2015). The exceptional waterproofing of ducks and other waterbirds may mean that the sub-plumage humidity is higher in these birds than in terrestrial taxa. Although, a study of cutaneous evaporation in pigeons found that the feather coat and the associated layer of still air together accounted for 6.2 - 25.8% of the total vapor resistance (Webster et al. 1985), suggesting that increased humidity under the feathers may be a general phenomenon.

How might this guide decisions about which band type is best as a weak link? Given that the humidity levels beneath the feathers can differ from the surrounding air, the performance and durability of a given band type may be affected by the sub-plumage humidity levels. Some rubber materials, such as TPU, may be sensitive to small changes in humidity even when temperature remains relatively constant and Silicone could start to embrittle in low humidity and persistently high temperatures, with small fluctuations in humidity increasing likelihood of failure.

However, it is worth noting that while significant correlations between temperature, humidity, and material survival were found, neither temperature nor humidity were precisely controlled as even in the CT room, temperature and humidity fluctuated in a random manner over time. It is therefore possible that these parameters might have been conflated with time e.g. if temperatures warmed outdoors during the timeframe of the trial. A more robust experimental set-up would involve replicates of the material survival experiments, under carefully controlled temperature and humidity conditions.

4.2.3. Rubber bands: effects of load

In the CT room, increasing load had a significant negative effect on the survival time of the Silicone bands, which may be because dry conditions can embrittle Silicone rubber (Oldfield and Symes 1996), causing the Silicone chains to become more rigid and less flexible; an effect that could be exacerbated by increasing loads.

Load had a significant negative effect on the survival time of the Natural Rubber bands in the natural weathering experiments, but not the CT room. This demonstrates that the effect of load varies depending on the other stressors. Natural Rubber is known to be subject to chain scission; a decay process in which the polyisoprene chains become gummy and weaker, exacerbated by the formation of free radicals, which develop more readily in the presence of UV light. The lack of UV light in the CT room may explain why the Natural Rubber bands survived longer there overall because, although the free radicals form as part of oxidisation generally, the exposure to UV radiation speeds up the decay process.

This has implications for how bands are integrated into harnesses, because as the materials become more exposed to and degraded by atmospheric conditions, the effect of load becomes increasingly damaging. This could be utilized to increase likelihood of early failure if a sufficient load could be applied to the weak link, with heavier loads reducing survival time.

4.2.4. Rubber bands; the effects of UV and other unmeasured factors

In general, the samples exposed to natural weathering had much shorter survival times than those in the CT room, which may be attributed to several unmeasured factors. The adverse impact of ozone and ultraviolet (UV) light on the longevity of elastomers is well-recognized, and it seems likely that UV, in particular, reduced the survival time of naturally weathered samples. The samples in the CT room were stored in a dark environment, and as such, were not exposed to UV light. Ozone concentrations are also typically, lower inside compared to outdoor environments (Huang et al. 2019), unless there is direct access to the open air or electrical equipment that leads to localized ozone accumulation. However, the probability of such ozone build-up occurring within the CT room is considered remote. Nevertheless, it should be considered that some countries have much higher ground level ozone than others (Sicard 2021) and this would certainly contribute to earlier failure than deployment in a place with low ozone levels (Lewis 1986). Bacteria can degrade rubbers, even vulcanised rubber, (Rook 1955, Rose and Steinbüchel 2005) but it is unknown as to whether this would have impacted the samples to any great degree over their short survival time.

In this experiment, feather colour had no significant effect on the survival time of the rubber bands used in the harnesses. Nonetheless, research has demonstrated that feather colour affects the transmission of UV light, with darker feathers blocking more UV than light-coloured feathers (Nicolaï et al. 2020, Wolf and Walsberg 2000). The amount of ultraviolet (UV) radiation can also vary based on factors such as latitude, altitude, time of day, weather conditions, and the presence of the ozone layer. UV radiation tends to be stronger near the equator and at higher altitudes, with Earth's highest levels recorded in the Andes(Liley and McKenzie 2006). Reflection off the surface of water increases UV exposure which, again, could affect survival times, depending on plumage colour and UV light levels, being most relevant for pale birds operating in high UV environments e.g. pale, tropical seabirds or high-altitude dwellers, such as the Andean Flamingo (*Phoenicoparrus andinus*).

4.3. Adhesives

4.3.1. Adhesive type; Overall performance and interactions of environmental stressors

The differences in survival times highlights the significance of adhesive type and bonding mechanism in their durability. Evo-Stik Impact, a polychloroprene rubber-based adhesive, had a relatively short survival time in both the natural weathering and CT Room trials and was sensitive to loading, despite having the highest initial shear strength. UHU Universal, a polyacrylate adhesive, demonstrated better longevity in natural weathering conditions despite having the lowest shear strength among the adhesives tested and may have had even better longevity had it been applied to a porous adherend (UHU Universal has a solvent-based polyacrylate formula, which forms a bond by penetrating the pores or irregularities of the substrate and creating hydrogen bonds).

Gorilla Glue Contact Clear, a silane-based adhesive, showed the longest survival time in both the natural weathering and CT Room analyses. The chemical composition, which includes silane-based components, provided excellent resistance to environmental factors, temperature, humidity, and mechanical stress. The combination of mechanical interlocking and chemical bonding mechanisms in Gorilla Glue Contact Clear contributed to its extended durability, while the specific limitations of the polychloroprene formulation in Evo-Stik Impact, such as limitations in withstanding mechanical stress, may have influenced its shorter survival time.

However, long duration is not always needed, and predictability can be far more important with harness release. The narrow range of survival times for the Evo-Stik applied to brass, made it more predictable for short term deployment in a harness. In contrast, the unpredictability of UHU survival time demonstrates its unreliability if used as a drop off mechanism. Although the extreme variability of UHU (compared with Evo-Stik) may also be due in part to the use of a sub-optimal i.e. non-porous adherend.

4.3.2. Adhesives; effect of temperature and humidity

The effect of temperature on survival times was not straightforward. Temperature had a significant negative effect on the survival time of the adhesives in the CT room, but it had no effect on the survival time in the natural weathering trial. This is counter-intuitive, given that temperatures showed much greater variation outdoors. It may be that there is an interaction between temperature and humidity, with the combination of the CT room's lower humidity levels and warm temperatures compromising adhesive durability.

There is some evidence that humidity does increase durability, as in the natural weathering trials, humidity had a significant positive effect on the survival time (for every 1% increase, survival time increased by 1.3 days). The fact that humidity did not have a significant effect on adhesive survival time in the CT room could be due to the limited range in humidity values in this environment.

Overall, the silane-based adhesive properties of Gorilla Glue Contact Clear seem to provide excellent resistance to changes in temperature and humidity, ensuring durability and bonding strength over an extended period. This should also be the case in a sub-plumage environment with a higher and narrow temperature range of 36-44 °C. However, given that the ultimate survival time is unknown (> 1 year), the effects of temperature and humidity as the adhesive degrades, are unquantifiable.

4.3.3. Adhesives; effect of load

Evo-Stik Impact, despite having the highest shear strength, was the only adhesive that showed a negative response to increased load, indicating its limitations in withstanding mechanical stress over time. If Evo-Stik impact was to be considered as a weak link, it is likely that interference by the bird may accelerate failure. These properties make it more suitable for use where an initial high strength is needed but an early drop off is required (within the range of ~50-120 days using the adherend in these trials).

Both Evo-Stik Impact and UHU set into a much more rigid form than Gorilla Glue contact Clear, which remained reasonably flexible. This flexibility could ameliorate the effects of load to a certain degree, as a stronger but more brittle adhesive may crack and break prematurely. Despite this, the relatively narrow range of survival times demonstrated by the Evo-Stik Impact in both experiments, shows it could be considered for live bird trials not expected to last longer than 100 days. UHU Universal, in contrast, demonstrated a larger range of survival times in both tests, indicating considerable variation and thus a greater difficulty estimating survival times. The ultimate survival time of Gorilla Glue Contact Clear is difficult to predict because all samples were still viable after a year had passed. However, load caused by movement and interference by a live bird may lead to shorter survival times for all adhesives.

4.3.4. Adhesives; the effects of UV and other factors

Similarly to rubber bands, adhesives can also be degraded by factors that were not measured in these experiments. When exposed to direct or prolonged UV light they can undergo degradation, leading to reduced bond strength and overall durability (Specialchem 2023). Ozone and exposure to chemicals or pollutants in the environment could also potentially weaken the bond and contribute to adhesive degradation over time. However, the samples tested were sandwiched between two plates of brass, limiting their exposure to UV light, even when exposed to natural weathering, making it more likely that their survival times were affected by moisture and humidity variations, substrate compatibility and the mechanical effects of load.

Although the study considered the effects of humidity, variations in moisture content (the amount of water in liquid form) could have more subtle effects on adhesive performance. Moisture fluctuations may lead to expansion and contraction of an adhesive, affecting bonding integrity. Silane containing adhesives, such as Gorilla Glue Contact Clear, being more suited to withstand such variations due to the trimethoxyvinylsilane content improving adhesion to substrates (Walker 2003).

Whilst the study considered the effect of load, the specific dynamics of the sample movements, especially in the wind and rain, could impact the adhesives differently and adhesives with higher load capacity and better resistance to mechanical stress may perform better in this context.

5.0. Conclusions

The results demonstrate notable differences between adhesives and elastomers, with adhesives having higher survival in all cases. There were also substantial differences within adhesives and elastomers that enabled Evo-stik, TPU and Natural Rubber to be identified as good candidate materials on the basis of predictable failure times for periods of 10 to > 100 days (noting that these durations relate to the specific conditions tested in this study). In terms of identifying materials more generally, it is important to note that breaking stress alone may not accurately predict the overall durability or performance of rubber bands, whilst the flexibility of adhesives is a critical factor in their ability to withstand repeated mechanical stress; flexible adhesives tend to exhibit greater resilience, while their rigid counterparts are prone to cracking when subjected to movement or heavy loads.

The work in this thesis could be extended in a number of ways. For instance, future research could expand on the insights gained from the experiments in Section 3.1 and 3.2 and investigate methods to deliberately stress and damage rubber bands. The substantial impact of knotting on the breaking strain suggests that this would be a potentially simple yet effective way of decreasing the survival time. Another potential area of experimentation would be to build on the concept of knot tension as a potential stressor, for example, varying the tension of knots tied in the elastic bands and the type of knot used, to simulate various levels of mechanical stress and loading. Further trials could usefully assess the extent that such manipulations might reduce the survival time and the predictability of the point of failure.

Another key parameter that could be varied in future trials could be the cross-sectional area of the bands. It seems intuitive that thicker materials would offer enhanced durability and longer survival times, but it is unclear how sensitive survival time might be to cross-sectional area. Nonetheless, increasing the cross-sectional area beyond a certain point may require bands to be incorporated into harnesses in a different manner to that used in the current trials.

Finally, exploring the effect of provenance on rubber band performance, i.e. factors such as age, storage conditions, batch variation, and manufacturing tolerances, represents an interesting area of inquiry. Unfortunately, in this study, it was extremely challenging to obtain any of this information from the manufacturers/importers. However, by systematically evaluating the impact of provenance factors on material properties, key variables that influence survival times, and their predictability, could be quantified.

In the case of adhesives, surface preparation and substrate material could be varied, as this is critical for bond strength and durability. Indeed, it would be interesting to evaluate how deviation from manufacturers recommendations on preparation techniques or substrate use impacts the survival time and predictability of failure in adhesives. Notwithstanding this, the results in this thesis will hopefully raise awareness of the ability to design low-cost weak-links that enable high quality data to be collected on bird movements and behaviour for a predetermined period, whilst also providing a predictable harness release for the benefit of bird welfare.

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Appendices

Supplementary Table 1 – Morphometrics of birds used in experiments

Bird ID	Sex	Body mass at start of study (g)	Body mass at end of study (g)	Tarsal length (mm)	External keel length (mm)	Feather Colour
p2	M	300	310	27	61.1	Dark
p4	M	260	290	29.1	61.4	Dark
p18	F	260	270	31.4	63	Light
p9	F	320	320	30	65.1	Light
p11	M	300	320	31.9	65.1	Dark
p13	F	330	340	32.9	70.1	Dark
p16	M	340	340	29.9	63	Light
p7	F	360	370	31	71	Light
p6	M	360	370	33	76	Dark
p14	F	350	340	33.7	69.5	Dark

Supplementary Tables 2 a & b – Sub plumage temperatures of birds used in experiments

2 a - Air Temperature 14 °C, relative humidity 40.1%

Bird ID	Sex	Axilla	Groin	Interscapular	Breast
p2	M	38	38	35	39
p4	M	39	40	36	37
p18	F	41	40	36	39
p9	F	40	41	35	39
p11	M	39	40	35	38
p13	F	39	39	36	38
p16	M	40	38	36	38
p7	F	39	38	35	39
p6	M	38	40	36	38
p14	F	38	40	34	38

2 b – Air temperature 20 °C, relative humidity 52%

Bird ID	Sex	Axilla	Groin	Interscapular	Breast
p2	M	38	39	36	39
p4	M	41	40	36	40
p18	F	41	41	36	38
p9	F	38	41	36	39
p11	M	39	40	35	38
p13	F	39	40	35	38
p16	M	40	39	36	39
p7	F	39	39	35	40
p6	M	39	39	35	40
p14	F	38	40	37	38

Properties of rubbers and adhesives used in these experiments.

Synthetic rubbers

There are many formulations of synthetic rubber, which are chiefly formed from the polymerisation of petroleum-based monomers (Blackley 2012, Wood 1940). This class includes rubbers such as polybutadiene (PBS) and polychloroprene (Neoprene™) (Fakirov 2017, Johnson 1976). There are also the silicon-based polysiloxanes (silicone rubber) (Mark et al. 2005) and thermoplastic elastomers (Claisse 2015) which are latex-free elastic plastics, one of which is Thermoplastic Polyurethane (TPU). Of these synthetic rubbers only TPU and silicone were tested as part of this study, therefore only those types will be discussed further.

Thermoplastic Polyurethane (TPU)

TPU is a thermoplastic elastomer consisting of block copolymers which are formed by chains of polymerized monomers that can be extended using another species of monomer. It is made from diisocyanates and short-chain diols, which are the rigid constituents, and long-chain diols, which are softer parts of the matrix. The hard and soft segments that comprise TPU can be manufactured in different ratios to produce distinct characteristics depending on need and, when combined in varying proportions, they produce TPU's that can range from rigid to extremely elastic. TPU has no covalent bond but is crosslinked by complicated physical interactions in the compound (Stribeck et al. 2017) and its semi-crystalline structure can be influenced by changes in temperature and humidity (Boubakri et al. 2010). Depending on the formulation of aliphatic and aromatic chemicals, soft TPU elastomers, such as elastic bands, have a recommended working temperature range from -65 °C to 200 °C (BASF 2022, Wölfel et al. 2020), good elasticity across their operating temperature range and are resilient to oils and greases. Aromatic TPU's are flexible and highly hygroscopic (Lukkassen and Meidell 2003), but the level of hygroscopicity depends on the chemical composition. TPU can also be degraded by UV light (Omnexus 2022) but is quite resistant to ozone.

Silicone Rubber

Silicones are a type of synthetic polymer that are produced through complex processes involving the compounding of siloxanes with other chemicals (Polmanteer 1988) and curing them to form polysiloxanes, commonly known as 'silicone' rubbers (Doede and Panagrossi 1947, Mark et al. 2005). The resulting material can be formulated in various ways to suit a wide range of applications, ranging from automotive to home baking. Unlike other types of rubber, silicone rubber contains Silicon-Oxygen bonds rather than the Carbon-Carbon and Carbon-Hydrogen bonds of other rubbers (LeVier et al. 1995), and this unique molecular structure imparts exceptional stability and resistance to environmental factors such as UV, ozone, and oxidisation (Kole et al. 1994). Silicone rubber is hydrophobic and durable but has limited resistance to acids, solvents, and petroleum oils. The operating temperature range of silicone rubbers varies depending on the formulation, with some having a range of -60 °C to 300 °C and, despite good tensile strength, their tear strength is generally considered poor, especially when compared to Natural Rubber (Shit and Shah 2013). Silicone is resistant to UVA and ozone but UVB, present in 5% of sunlight, can rupture the Si-O molecular bonds, causing premature failure (Wang et al. 2021).

Natural Rubber

Natural Rubber is formed from latex, a botanical exudate. It is a protective substance that is generated from specialized cells, called laticifers, varieties of which can vary between species (Tan et al. 2017), with the Rubber Tree (*Hevea brasiliensis*) being the most notable. Natural rubber consists almost entirely of the cis-1,4 structure (CH2=C(CH3)—CH=CH2) in stereoregular chain units and the aliphatic polyisoprene molecules contain thousands of strands that stick together by forming electrostatic bonds allowing the fibres to stretch to several times their normal length and recover. In its unstretched form, the polymer chains of natural rubber are disordered and amorphous, but when tensile stress is applied, the molecules can stretch several times their normal length, and form into a more ordered, crystalline arrangement, strengthened by crosslinked bonds. Without the vulcanisation process of crosslinking, whereby sulphur molecules bridge the chains of isoprene, the rubber would easily become too pliable, stretchy and gummy in warm temperatures, and brittle and crumbly as temperature decreases. The more sulphur crosslinks in the mixture; the stiffer the rubber becomes. Stationery-type natural rubber bands have minimal crosslinking, so they retain their elasticity, but this also makes them less durable than more rigid rubbers with greater crosslinking.

The recommended operating temperature of Natural Rubber is approximately between -50 °C and 82 °C (Vijayaram 2009) but again, this is very dependent on formula. Temperatures outside this range will make the rubber degrade much more quickly. Natural Rubber is not inherently hydrophobic and can absorb water, but experiments with submersion have found minimal negative effect on survival (Le Gac et al. 2015) depending on formula and treatment, such as adding hydrophobic agents.(Paul and Robeson 2008, Trakuldee and Boonkerd 2017), though these are generally reserved for more specialist applications. Natural Rubber is seriously degraded by ozone and UV light.

Adhesives

Evo-Stik Impact

Contact adhesives require an application to both adherends and a period of drying onto the substrate before being married together, forming a strong bond. The most common contact adhesives have a neoprene, or other rubber base, dissolved in a solvent. Evo-Stik Impact is a contact adhesive formulated by dissolving polychloroprene rubber and other compounds in a solvent liquid. The volatile solvent evaporates, leaving behind the rubber adhesive. Once cured, it has good bond strength and is generally resistant to heat, oxidation, water, solvents and other chemicals. Additives are used to stabilize the compound and impede degradation (Comyn 2021). Evo-Stik Impact has a working temperature of 5°C to 55°C once cured and is listed by the manufacturer as being suitable for bonding wood, MDF, laminate, metal, PVC, cork, leather, rubber, glass, mirror, stone, and ceramics (Bostik 2015). It is classified by the manufacturer as water-resistant, but polychloroprene is negatively affected in the long term by exposure to UV light.

UHU Universal.

UHU Universal adhesive is polyacrylate, which is a type of thermoplastic. The adhesive is made from a polyvinyl acetate dispersion in alcohol and esters. As with the contact adhesive, it dries by evaporation of the volatile component, leaving the polyacrylate resin bonding agent. According to the manufacturer, it has good water and moisture resistance, though not waterproof, is suitable for bonding a variety of materials and has a working temperature range of 5 °C to 70 °C once cured (Bolton 2022).

Gorilla Glue Contact Clear.

As mentioned, when discussing silicone rubber bands, silane-based rubbers are generally resistant to extremes of temperature, UV radiation, and oxidation (Dean 1990), and they perform well in wet conditions. Adhesives containing these compounds have higher shear strength than silicone sealants, due in part to other crosslinking additives, but lower strength than epoxies or acrylates (Sibuea 2014) and, once cured, retain flexibility. Similar to other contact adhesives, the solvent base evaporates, leaving the adhesive component to form a bond. Gorilla Glue Contact Clear is listed by the manufacturer as being suitable to bond many materials. It is water resistant and has an operating temperature of -20 °C to 50 °C (Gorilla 2022).

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