Smart Cellular Systems with Pressure Dependent Poisson's Ratios

D. Attard[1], **R. Cauchi**[2], **R. Gatt**[1], **J.N. Grima-Cornish**[1], **J.N. Grima**[1,3*]

[1] *Metamaterials Unit, Faculty of Science*
University of Malta, Msida, MSD 2080, Malta

[2] *Department of Chemistry*
University of Malta Junior College, Msida, MSD 1252, Malta

[3] *Department of Chemistry, Faculty of Science*
University of Malta, Msida, MSD 2080, Malta
[*] *E-mail: joseph.grima@um.edu.mt*

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Abstract: The Poisson's ratio behaviour of cellular systems which change their internal features when subjected to pressure change to become a "re-entrant" or "non-re-entrant" honeycomb was investigated. It was shown, through finite elements simulations, that these changes in geometry permit the systems to exhibit a wide range of Poisson's ratios, the magnitude and sign of which can be controlled through the external pressure. Auxetic behaviour was also shown to be obtainable at specific pressures with the right combination of design and materials.

Key words: mechanical metamaterials, auxetic, negative thermal expansion, negative Poisson's ratio

I. INTRODUCTION

The evolutionary process has provided mankind with an endless source of inspiration for optimisation of systems for specific applications. From the materials science perspective, honeycombs and cellular solids, that is "an assembly of cells with solid edges or faces, packed together so that they fill space" [1] are probably the best example. Their "cost" to "properties" ratio is second to none, and their development has made it possible to fabricate various low-weight/low-cost products with excellent mechanical properties. More importantly, they have permitted the advancement of various industrial sectors in a manner that would never have been possible without their use. Suffice to mention their extensive adoption in the transport industry where they are used in the manufacture of airplanes, boats and other nautical vessels, automobiles and even bicycles.

The term "mechanical metamaterials" can be used to describe a wide of range of artificial systems that achieve their properties from their structure rather than their chemical compositions and typically exhibit some unusual mechanical response. These include systems exhibiting a negative Poisson's ratio (auxetic behaviour, a term which is now in common usage and translated to many languages including Maltese, see Appendix A) [1–66] or negative compressibility [65–77]. The use of honeycombs and other cellular solids in this field of research is not something new, with several publications [17–29] originating much before the term "mechanical metamaterials" was actually coined. With time, such "mechanical metamaterials" in the form of cellular systems became increasingly more versatile and multifunctional, and capable to respond to various stimuli [16, 55–64, 78–80]. A particular design of cellular solids which was recently investigated in detail is the one depicted in Fig. 1, where it was shown that, through careful choice of various geometric parameters and the materials used, it is possible to engineer systems which can exhibit both negative thermal expansion and temperature-tuneable Poisson's ratios [59, 60]. These systems work on the principle that bi-material strips made from constituent materials A and B bend when subjected to changes in temperature [81] as a result of dissimilar thermal expansion coefficients α_A and α_B (see Fig. 1). This was, in fact, verified through the use of finite-element simulations which has looked at various such e-prototypes made from common materials such as steel and zinc. It was also shown that the same systems, if made from materials having sufficiently and appropriately different intrinsic compressibility β_A and β_B (due to a differences in stiffness/Poisson's ratio, see Fig. 1) [82], could change their shape when subjected to a change in pressure (e.g. become re-entrant) and in the process exhibit rather interesting compressibility properties including negative linear compressibility [59].

The present work will re-investigate the system shown in Fig. 1, this time with the scope of assessing whether these systems can be made to exhibit pressure dependent Poisson's ratio properties. In particular, an attempt will be made to propose protocols how the systems can be made to exhibit tailor-made auxetic behaviour through a change in pressure. The motivation for this work is that whilst several other studies have looked at macroscale systems which exhibit temperature tuneable Poisson's ratio [60–62], less work has been done on systems which can be constructed at the macroscale which can have their geometry and Poisson's ratio properties tuned true a change in pressure. This is rather unfortunate since pressure, like temperature, is one of the rather few environmental conditions which may be externally controlled and may need to be taken into consideration when carrying out experiments.

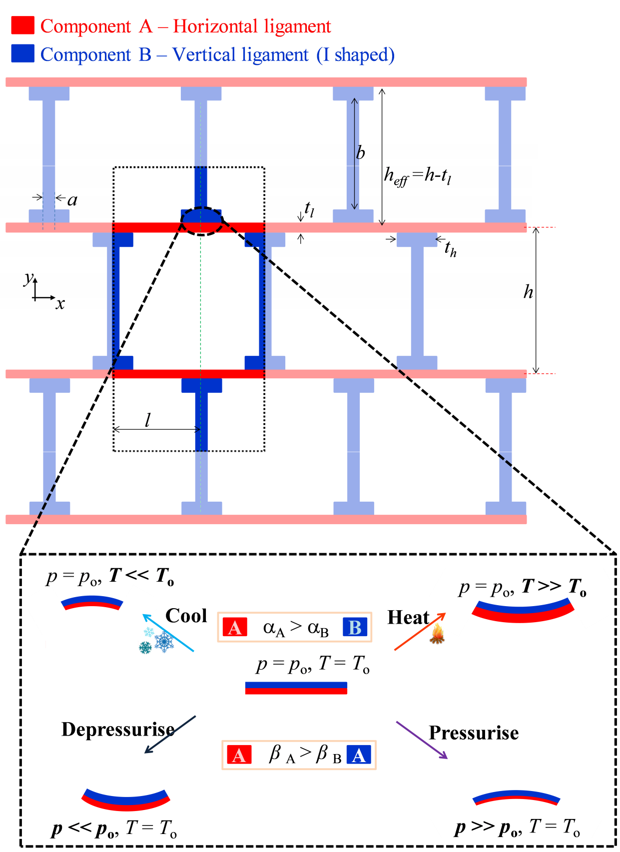


Fig. 1. The proposed system which can exhibit negative thermal expansion/negative linear compressibility upon a change of temperature (T)/pressure (p) as it becomes re-entrant or non-re-entrant [59]. This system was also shown to exhibit temperature dependent Poisson's ratio properties [60]. T_o and p_o refer to the reference temperature/pressure

II. SIMULATIONS

The cellular system depicted in Fig. 1 was studied via Finite Element (FE) simulations using the software ANSYS as this was subjected to uniaxial strain at various extents of hydrostatic pressure. The aim of these simulations was to study in a qualitative and quantitative manner the Poisson's ratio properties as a function of pressure (or change in pressure). The boundary conditions applied are as specified in Cauchi (2020) [59] where a more detailed description of these systems, including their ability to manifest negative compressibility, as well as negative thermal expansion, is presented.

Unless otherwise stated, Materials A and B were assumed to be isotropic and assigned Poisson's ratios of 0.3 and Young's moduli of $E_A = 82.74$ MPa and $E_B = 3309.00$ MPa, respectively. These values were arbitrarily chosen and assumed to be constant over the whole pressure range applied. Unless otherwise stated, the geometric parameters related to the vertical ligaments were $h_{eff} = 10$ and $t_h = 2$, whilst for the horizontal ligaments t_l was set at 0.2 with $l = 10, 20, 30$. All lengths are in millimetres. These systems were first solved linearly for pressure changes of ± 0.5 MPa, ± 1.0 MPa, ..., ± 3.0 MPa in an attempt to simulate the behaviour over a wide pressure range. The procedure used for these simulations has been well validated as described in more detail elsewhere [59]. The `upgeom` command in ANSYS was then used to update the geometry of the model to that of its deformed configuration according to displacement results at the applied pressure. The system so obtained is taken to be the "original" system used in the calculation of the Poisson's ratio at that particular pressure p as this corresponds to the system at the simulated pressure p with no additional applied mechanical strain.

The effect of uniaxial strain in the horizontal x-direction on this updated model was then studied by performing an additional linear FE analysis while the system was subjected to an additional uniaxial compressive strain of -0.1% in the x-direction. Note that compressive strains in the x-direction were applied (rather than tensile) as a compressive strain is not expected to deform the system in a manner which would change its re-entrant or non-re-entrant nature. Similarly, to study the effect of loading the vertical y-direction, a compressive strain of $+0.1\%$ was applied in the y-direction for systems which had a re-entrant geometry (to ensure that the re-entrant shape was preserved) whilst a tensile strain of -0.1% was applied in the y-direction for systems which had

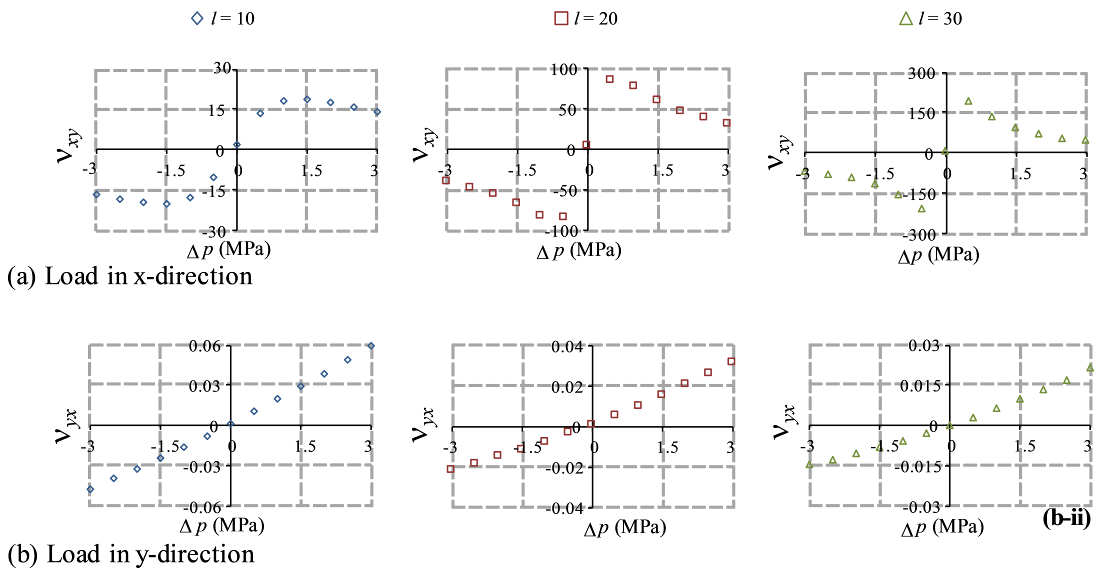
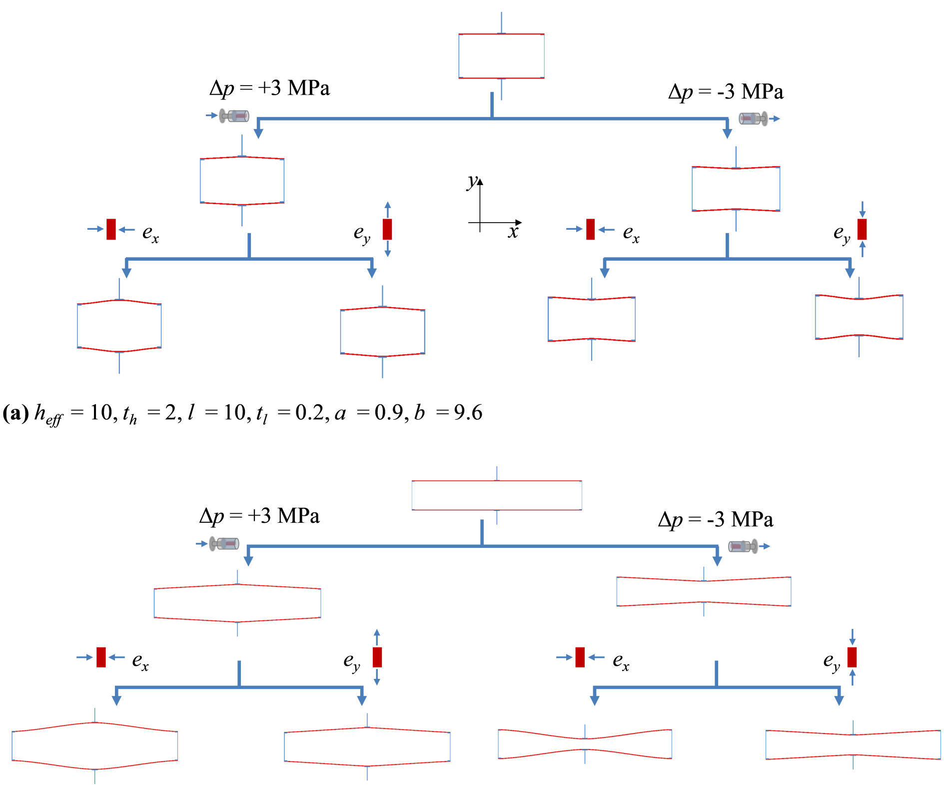


Fig. 2. A quantitative report of the results



(a) $h_{eff} = 10, t_h = 2, l = 10, t_l = 0.2, a = 0.9, b = 9.6$

(b) $h_{eff} = 10, t_h = 2, l = 30, t_l = 0.2, a = 0.9, b = 9.6$

Fig. 3. A qualitative report of the results when subjected to an increase in pressure ($+ve\ \Delta p$) or a decrease in pressure ($-ve\ \Delta p$)

non-re-entrant geometries (to ensure that the non-re-entrant shape was preserved). The engineering Poisson's ratio ν_{xy} and ν_{yx} at a given pressure was then calculated using the protocol described in Grima-Cornish et al. (2020) for a similar study with temperature as a variable instead of pressure [60].

III. RESULTS AND DISCUSSION

The results of simulations performed in an attempt to study the effect of pressure on the geometry and Poisson's ratio are summarised in Figs. 2 and 3. More specifically,

Fig. 2 shows the simulated Poisson's ratio for the various systems studied as a function of the applied change in pressure. To aid the interpretation of these results, a representative qualitative result is presented in Fig. 3 in the form of images of two typical systems as these are first subjected to a change of pressure and then, with the pressure still applied, uniaxial loading in the x- or y-direction.

The results in Fig. 2 clearly show that the sign of the Poisson's ratio is dependent on whether there is an increase in pressure or a decrease in pressure whilst Fig. 3 shows that the systems are essentially behaving like hexagonal re-entrant ($-ve\ \Delta p$) or non-re-entrant honeycombs ($+ve\ \Delta p$). The Poisson's ratios can be correlated to whether the system at a particular pressure is re-entrant on non-re-entrant, with all the re-entrant systems studied exhibiting a negative Poisson's ratio for loading in both the x and y directions whilst all the non-re-entrant systems exhibit a positive Poisson's ratio. Furthermore, it is evident that the exact magnitude of the Poisson's ratio is dependent on the geometry of the systems which in turn is dependent on the pressure at which the Poisson's ratio is measured. A general trend is that the Poisson's ratios for loading in the x-direction are much higher in magnitude than those in the y-direction, to the extent that they can even be called "giant Poisson's ratio". These gigantic values apply for both the auxetic and non-auxetic systems and are retained over a wide range of pressures.

Having recognised that these systems are essentially behaving like hexagonal re-entrant or non-re-entrant honeycombs, these trends in the Poisson's ratio shall first be interpreted though the model formulated by Gibson and Ashby for flexing hexagonal honeycombs, or its equivalent, formulated by Evans et al. (1995) [22] and Masters and Evans (1996) [26] and for hinging honeycombs. Referring to Fig. 4a, these models state that, assuming idealised flexing or hinging behaviour, the Poisson's ratio may be approximated by:

$$\nu_{xy}^{\mathrm{f,h}} = \frac{1}{\nu_{yx}^{\mathrm{f,h}}} = \frac{\cos\theta}{\sin\theta}\frac{X}{Y} = \frac{l\cos^2\theta}{(h+l\sin\theta)\sin\theta} = \frac{\cos^2\theta}{(h/l+\sin\theta)\sin\theta}\ , \tag{1}$$

where the parameters h and l may be assumed to be as defined in Fig. 1 whilst, with this combination of materials, referring to Figs. 3 and 4, the angle the angle θ needs to be approximated, where:

- $\theta = 0$ when $\Delta p = 0$ (the reference system where the horizontal ligament is straight);
- $\theta = -ve$ (negative) when there is a decrease in pressure (corresponding to a re-entrant honeycomb); $\theta = = +ve$ (positive) when there is an increase in pressure (corresponding to a non-re-entrant honeycomb).

This simple yet powerful model (assuming flexure/hinging type of deformation) can explain a number of characteristics in the behaviour including some trends in Poisson's ratios and why ν_{yx} assume small values whilst ν_{xy} assume gigantic values.

As shown in Fig. 3, the pressure changes applied only result in small changes in θ, (i.e. θ is close to zero). Thus, according to the honeycomb flexing/hinging model, the Poisson's ratio for loading vertically can be approximated by:

$$\nu_{yx}^{\mathrm{f,h}} = \frac{[h/l+\sin(\theta)]\sin(\theta)}{\cos^2(\theta)} \approx \frac{h}{l}\theta, \tag{2}$$

since for small angles, $\sin(\theta) \approx \theta$, $\cos(\theta) \approx 1$, $h/l >> >> \sin(\theta)$. Through this equation, it is evident that ν_{yx} will assume very small values, close to zero, as $\theta \to 0$ (as is the case in this present work). The same expression can also explain the trend of a *qausi* linear relationship between ν_{yx} and p, since if one had to assume that θ in the analytical model varies *quasi* linearly with pressure, then a linear relationship between ν_{yx} and p would follow. All this is further supported

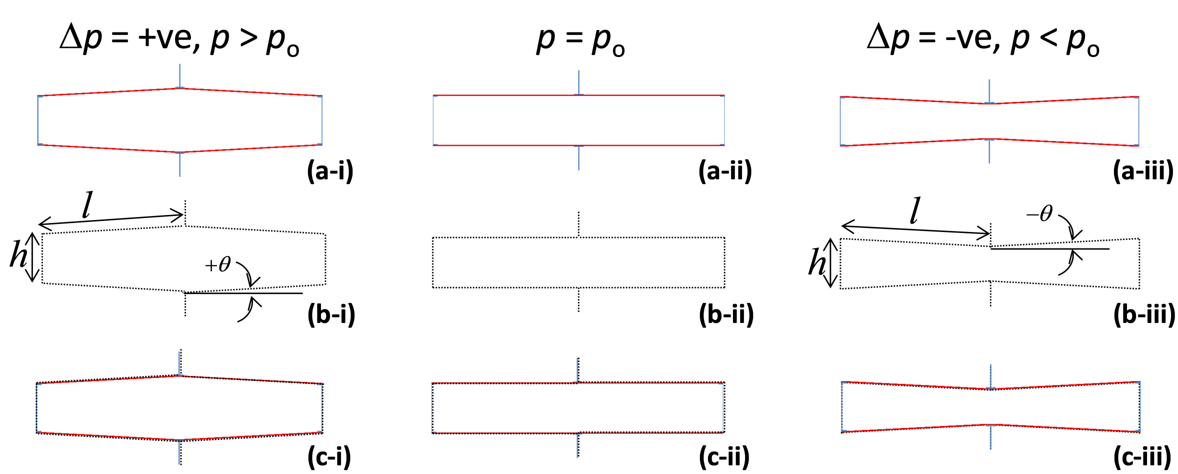


Fig. 4. A "fitting" of the hexagonal honeycomb onto the simulated systems under different pressures

by the observation that the gradient is highest for the system when $l = 10$ (i.e. $h/l = 1$, the highest from the systems modelled), then $l = 20$ (i.e. $h/l = 1$) and then $l = 30$ (i.e. $h/l = 1/3$, the lowest from the systems modelled).

This honeycomb model can also explain some, but not all, of the results of the simulations for ν_{xy}. For example, recognising that this simplified analytical model (assuming flexure/hinging type of deformation) suggests that the systems studied are supposed to follow the relationship:

$$\nu_{xy}^{\mathrm{f,h}} = \frac{1}{\nu_{yx}^{\mathrm{f,h}}} \approx \frac{l}{h}\left(\frac{1}{\theta}\right), \tag{3}$$

it is clear to see why ν_{xy} are rather large, since, as discussed above, in this present work, θ is very small. This simple model can also explain the decay of the Poisson's ratio with changes in pressures at higher magnitudes of pressure, and why ν_{xy} is largest in magnitude when $l = 30$ (i.e. $l/h = 3$, the highest from the systems modelled) when the magnitude of the largest Poisson's ratio values exceed 10^2, then $l = 20$ (i.e. $l/h = 2$) and smallest when $l = 10$ (i.e. $l/h = 1$, the lowest from the systems modelled). This simple model cannot, however, predict the trends in the Poisson's ratios for the less extreme pressures where the analytical expression in eqn. (3) predicts that $\nu_{xy} \to \pm\infty$ as $\theta \to 0$. Instead, the results of the simulations are predicting that $\nu_{xy} \to 0$ as $\theta \to 0$, a result which was obtained consistently. To explain this behaviour, one needs to look more thoroughly at Fig. 3 to assess more closely the manner of deformation. Here it becomes evident that as $\Delta p \to 0$, the systems are such that their horizontal ligament is *quasi* perfectly straight. In such situations, it is not expected that uniaxial loading would result in any appreciable flexure/hinging type of deformation as the component of the force which lies orthogonal to such ligament would be excessively small. Instead, one would expect that deformations would be caused by simple stretching of these horizontal ligaments, which would give a Poisson's ratio $\nu_{xy}^{\mathrm{s}} = 0$ for an idealised stretching behaviour when the ligaments are perfectly straight ($\theta = 0$). In fact, the Poisson's ratio from the idealised stretching model as predicted by the model of Evans et al. (1995) is given by (with reparameterization, and simplification for small values of θ):

$$\nu_{xy}^{\mathrm{s}} = \frac{-\sin\theta}{\cos\theta}\frac{X}{Y} = \frac{-l\sin\theta}{(h + l\sin\theta)} = \frac{-\sin\theta}{(h/l + \sin\theta)} \approx -\frac{l}{h}\theta. \tag{4}$$

When expressions (3) and (4) are taken together, recognising (3) is expected to dominate at extreme pressures, with (4) only playing an important role when the horizontal ligaments are straight or *quasi* straight (stretching is generally a more energy expensive mode of deformation compared to flexure/hinging), then the trends in the results for ν_{xy} will all be well explained.

Before concluding it is important to highlight some of the strengths and limitations of this work. An obvious limitation is that this work is based on modelling using an idealised representation of a defect-free system where the materials and systems behave in a "perfect" manner. Should real prototypes be constructed, such level of perception may be difficult to attain. For example, real materials could debond at the interfaces, degrade, or exhibit pressure dependent properties. Also, whilst it is known that some plastics have properties which are similar to the ones used in this study, Materials A and B are purely hypothetical materials. Further studies are thus recommenced to carefully select which materials should be used, as well as further studies to further improve the design. In terms of modelling, obviously, more complex models, such as the use of nonlinear analysis, or comparison with analytical models where the vertical elements are replaced by rectangular units [12]), could also be applied to these system. Nevertheless, the main strength lies in the fact that the concepts employed are rather basic and thus not impossible to implement. Furthermore, by permitting the systems to act as open systems which can change their mass by exchanging content, the same effects could be achieved through a "soaking"/"drying" process where the fluid exerting the pressure would penetrate parts of the system, but not others, thus possibly resulting in bending of ligaments as a result of uneven "growth". In such cases of semi-permeable systems, the effects studied here, including the pressure-dependent Poisson's ratio could be even more pronounced. Obviously, this pressure-dependent Poisson's ratio could be a desired effect, where the system is specifically designed to behave in this manner, or an undesirable/unavoidable one, which happens due to changes in environmental conditions that are brought about by necessity (e.g. the unavoidable change in pressure when a sample is submerged under sea water or other extreme pressure conditions). Irrespective of which scenario it is, it is important that the effect of pressure is properly accounted for in the design process.

It must also be mentioned that what was modelled here represents just one example of many variations how this concept can be employed. For example, by simply reversing the materials (i.e. use Material A instead of B and *vice-versa*), it is expected that the exact opposite trend would be observed where auxeticity is manifested at increased positive hydrostatic pressure. Other designs could also be used, including ones in which the third physical dimension is also used. It can also be envisaged that this effect could be further enhanced through other additional stimuli, such as a change of temperature. It is obviously beyond the scope of this work to provide such an exhaustive analysis.

IV. CONCLUSION

This work has shown that it is possible to construct systems which could exhibit pressure dependent Poisson's ratios through the use of composite honeycombs which respond to changes in pressure by changing their shape. It was also discussed that, depending on the construction, the system could even exhibit negative Poisson's ratio of considerable magnitude. Given the practical advantages that such systems could offer, included but not limited to the benefits normally associated with auxetic behaviour, it is hoped that the present work would provide an impetus to other researchers to further develop the concepts presented here. In particular, it is hoped that this study is extended in a manner which looks in more detail at semi-permeable systems that can permit fluid to penetrate in parts, but not all, or the system. Such systems could exhibit an even more pronounced dependency on pressure, making the changes in Poisson's ratio even more remarkable.

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Appendix A: The term "auxetic" in Maltese

The term "auxetic" has been translated to various languages, one of which is Maltese, the national language of the authors. Quoting directly from Grima, Gatt & Zammit (2005)*: "The term *auxetic* derives from the Greek word αυξετοσ (auxetos) meaning *that may be increased*, referring to the width and volume increase when stretched (Evans et al. 1991). In modern Greek, we also find the word αυξάνω (auxano) meaning *to increase*. Since no equivalent word is available in the Maltese language to describe systems which experience a width increase when stretched, we propose that in Maltese, systems which expand when uniaxiually stretched will be termed *awksetiku* (singular masculine), *awksetika* (singular femine) or *awksetiċi* (plural). Thus for example, the terms *an auxetic material*, *an auxetic structure*, *auxetic materials* and *auxetic structures* will translate to *materjal awksetiku*, *struttura awksetika*, *materjali awksetiċi* and *strutturi awksetiċi* respectively." The contribution of Professor Oliver Friggieri, Professor of Maltese, University of Malta, for his help in coining these terms in Maltese fifteen years ago is gratefully acknowledged.

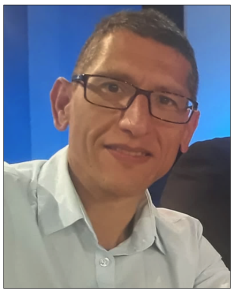
*J.N. Grima, R. Gatt, V. Zammit, A. Alderson, K.E. Evans, *On the suitability of empirical models to simulate the mechanical properties of alpha-cristobalite*, Xjenza **10**, 24–31 (2005).

Daphne Attard is currently a lecturer at the Faculty of Science at the University of Malta. She obtained her PhD in chemistry in 2011 from the same university. Since then, she has been working in the field of auxetic materials and other materials with anomalous properties including those with negative compressibility. Her research employs a variety of modelling techniques ranging from mathematical modelling of mechanical properties, finite element modelling and molecular modelling.

Reuben Cauchi obtained his PhD in chemistry in 2013 from the University of Malta. He currently lectures chemistry at the same university. His research interests include studying materials with anomalous thermomechanical properties, in particular auxetic materials and materials exhibiting negative compressibility. His research involves using a variety of modelling techniques, ranging from finite element modelling to molecular modelling.

Ruben Gatt is an Associate Professor at the University of Malta. He graduated in 2004 with a degree in Biology and Chemistry. He later obtained a Master degree and a PhD in Chemistry from the University of Malta. He has published over 100 peer review journal papers. The main research areas that he is currently pursuing include that of molecular modelling, mechanical metamaterials, polymerisation reactions and synthesis and characterisation of nanoparticles. Professor Gatt is a co-inventor of three patents filed in Malta, UK and Italy and one patent pending invention.

James N. Grima-Cornish graduated with a BSc (Hons.) in Chemistry with Materials from the University of Malta in 2019. His main fields of interest include molecular systems and metamaterials having negative and anomalous mechanical properties, which he investigates by means of analytical and computer simulations, and more recently physical experiments. Currently, his research is focused on the development and study of novel structures and materials having anomalous thermo-mechanical properties. He has co-authored a number of journal publications, three of which were featured as front covers. In 2019 he was awarded the Physical Crystallographer Group Award by the British Crystallographic Association and the Auxetics Young Researchers Award. James is a keen traveller with a passion for the arts and culture.



Joseph N. Grima is a Full Professor at the University of Malta within the Faculty of Science (Department of Chemistry and Metamaterials Unit). His academic work focuses on mechanical metamaterials from the perspective of geometry-function relationships. He leads a research group working on materials and structures exhibiting negative properties such as negative Poisson's ratios (auxetic), negative thermal expansion and negative compressibility. The group has hosted a number of international conferences and workshops and co-edited various international journal special issues on these novel systems. In addition to this, Professor Grima has a keen interest in biomechanics with a particular focus on rowing, a sport which he practices. He has published more than 150 ISI-cited journal publications. He is the founding and current President of the Malta Paralympic Committee.