

# **TWO NEW ENVIRONMENTAL BUILDING TECHNOLOGIES, ONE NEW DESIGN METHOD: INFRARED TRANSPARENT INSULATION, BIODEGRADABLE CONCRETE FORMWORK AND BioTRIZ**

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## *Abstract*

**Two new environmental building technologies have been developed to early prototype stage. The design method by which they were conceived is explained. The first technology concept is an infrared transparent insulation. The aim is to radiantly couple a building to the cool sky, while thermally isolating it from local ambient temperature and solar gains. There are several possible manifestations; preliminary tests saw radiator temperatures drop 5C below ambient temperature, suggesting scope for free cooling in hot climates. The second technology concept is a concrete formwork product made from biodegradable starch foam. It could have a better end-of-life profile than other formwork materials, such as polystyrene foam, which is used to form concrete elements with complex external and internal geometries, to perform a variety of functions. Tests indicate that the functional unit of starch foam could be improved by manipulating the geometry to give it greater stiffness and ‘flush-ability’ for less material. It is shown how the design method BioTRIZ was applied to key problems in the development of both concepts. BioTRIZ is supposed to facilitate the transfer of biological problem-solving principles to engineering. Both new technology concepts apply the same solution *Local Quality*.**

**Keywords: Building design, Radiative cooling, Starch expanded foam, Biomimetics, TRIZ**

## **1.0 Introduction**

Two new environmental building technologies have been developed to early prototype stage. The first technology concept is an infrared transparent insulation, which might be used to keep building fabrics in hot countries below ambient temperature without additional energy input. The second is a biodegradable concrete

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formwork, which may prove to have less environmental impact than current systems. It might also be used to improve the functional unit of concrete building elements, by forming complex internal and external geometries which perform multiple functions.

Key trade-offs in each of these new developments were resolved using a design method called BioTRIZ, which is supposed to facilitate the transfer of biological solutions to engineering problems [1]. It is based on the Russian system of engineering problem solving called TRIZ [2], which is supposed to facilitate the transfer of solutions across technological disciplines. Both new technology concepts are related by the solution *Local Quality*, which has been found to be an important biological ‘design’ strategy [1].

## 2.0 Infrared Transparent Insulation

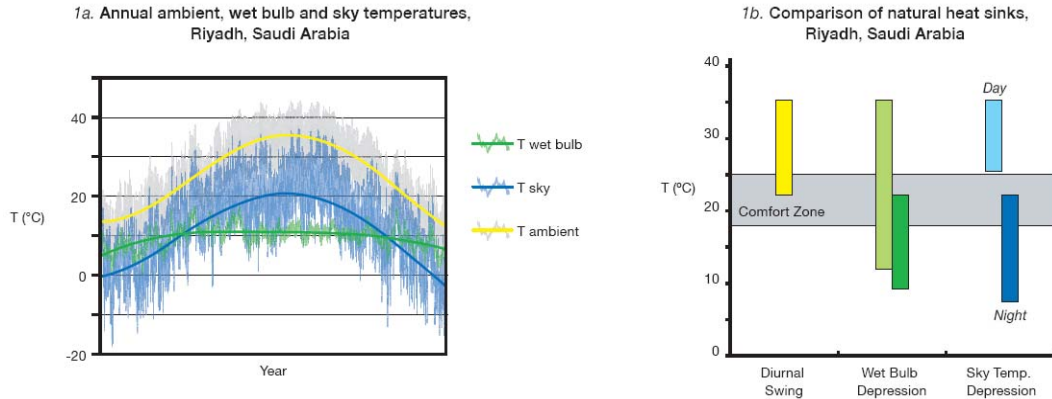
The sky – a very large ‘object’ with a low effective temperature – is often markedly cooler than the ambient temperature at ground level. The sky is at its coldest on clear, dry nights. The Persians were the first to utilize this phenomenon. By filling wind-sheltered troughs with water, they were able to make ice in ambient temperatures as high as 9C [3]. More recent radiative cooling techniques include solar thermal panels run at night to cool water close to sky temperature [4].

It is useful to think of the sky as a hypothetical blackbody radiating longwave infrared energy downwards. Thus it will have an equivalent sky temperature  $T_s$  (K), and the rate of radiative energy transfer  $R_{net}$  ( $W m^{-2}$ ) between a horizontal flat plate and the sky will be [5]:

$$R_{net} = \varepsilon\sigma(T^4 - T_s^4) \quad (1)$$

Where  $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} K^{-4}$ ),  $\varepsilon$  is the emissivity of the flat plate (dimensionless), and  $T$  is the temperature of the plate (K). The drier (water vapour), clearer (clouds) and cleaner ( $CO_2$ ) the sky, the colder it gets [6]. The difference between sky temperature and ambient temperature – the sky temperature depression – can be considerable, particularly in hot-dry climates. The greater this difference, the larger the scope for radiative cooling. Figure 1a shows the annual trends for ambient and sky temperature in Riyadh, Saudi Arabia. The dark blue column in figure 1b shows the average sky temperature depression during Riyadh summer nights. Both show that the scope for rejecting radiant heat into the sky is significant.

This free cooling resource can be used if a building is radiantly coupled to the sky, and thermally isolated from ambient and solar gains. In this way it is possible to cool a mass below ambient temperature, without additional energy input. A longwave infrared transparent insulation would enable this, but none seem to be commercially available. There are several possible manifestations using existing technology, for instance: a vacuum panel with infrared selective coating; a honeycomb panel with an infrared selective face; or even bundles of infrared fibre optics sprouting from a roof like animal fur [7].



**Figure 1.** When designing buildings for hot countries, it is important to make use of natural heat sinks. In a hot-arid climate such as Riyadh, the scope for evaporative cooling is large, as indicated by the low wet-bulb temperature. However water is scarce in this region. The low sky temperature offers an alternative – radiative cooling (see text).

## 2.1 Experiment

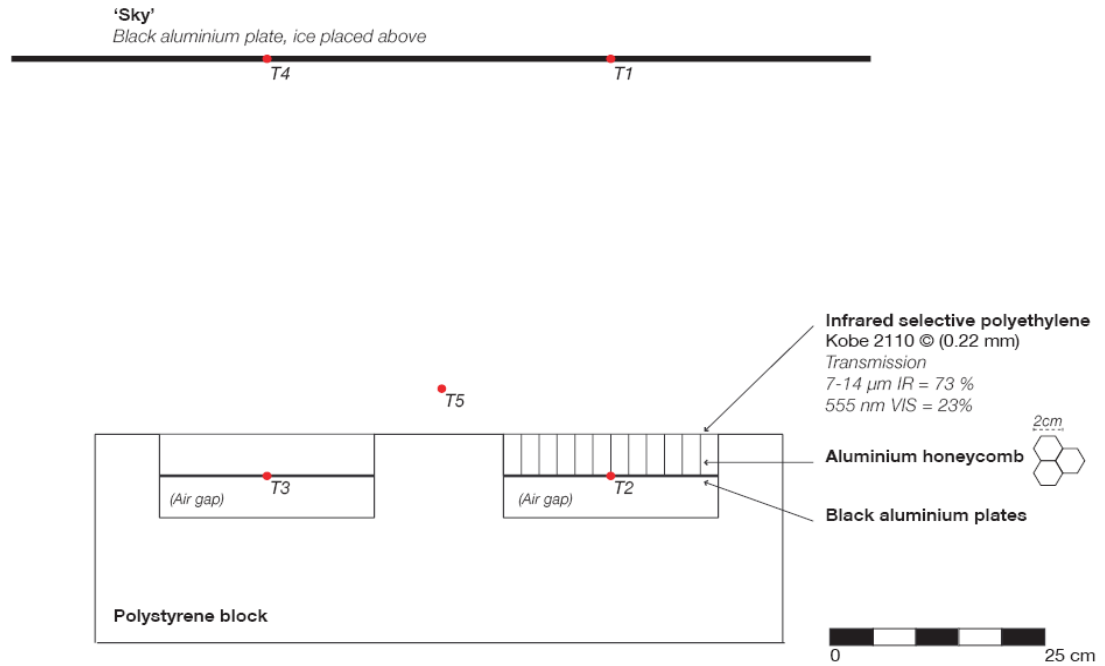
A preliminary experiment was set-up to gauge the radiative cooling effect, to provide a basis for further tests. Figure 2 shows the basic set-up. The object of the experiment was to see by how much the two black plates would fall below ambient temperature when in radiant contact with a cold black body, each with a different rudimentary infrared transparent insulation above it.

Each black aluminium plate was placed in an open top insulated box, so that there was 5cm of space below and above. An infrared selective filter material was put across the top of both boxes [8]. An aluminium honeycomb baffle occupied the air space between the plate and infrared material in one of the boxes. Aluminium was chosen because it is infrared reflective: the idea was that the cells would suppress counterproductive convection, but still give the radiator plate an infrared view of the cold body. A honeycomb also plays a useful structural role.

A large black plate cooled by ice was placed 50cm above both samples, to simulate the sky. Thermocouples were used to measure surface temperatures and ambient temperature. The experiment was undertaken in an uncontrolled indoor environment.

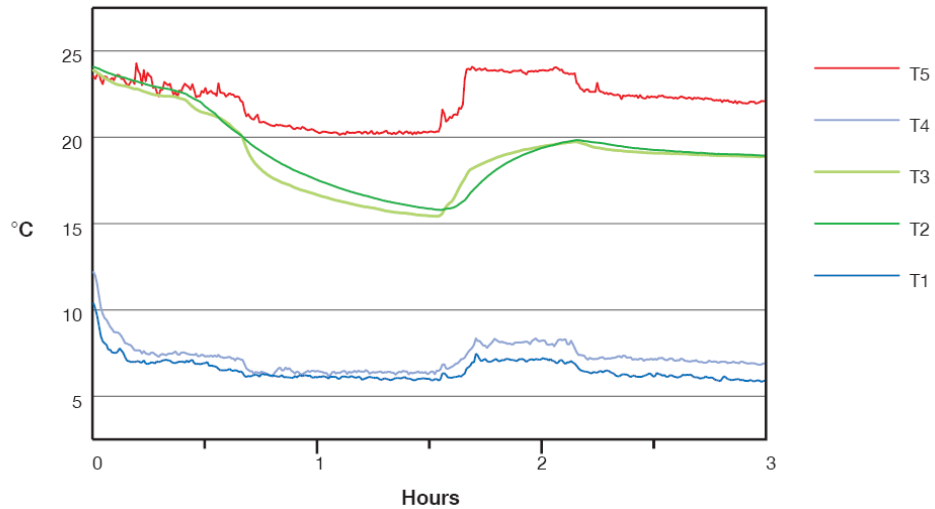
## 2.2 Results and discussion

Figure 3 shows the results of the experiment. The two plates began at ambient temperature. The black ‘sky’ was soon cooled to 7°C through contact with ice. At first, the rate of radiative cooling was slow. It soon became clear that the ‘sky’ was not big enough: warm objects around the room were in radiant view of the plates. The scaffold was wrapped loosely in aluminium foil to block this view. This reduced the ambient temperature near the samples, and increased the rate of radiative cooling. The temperature of the plates reduced until they started to stagnate near 15°C, 5°C cooler than ambient temperature.



**Figure 2** Radiative cooling experimental set up. The aim is to see how much cooler than ambient (T5) the black aluminium plates (T2, T3) get when in radiant contact with the cool 'sky' (T1, T4). The infrared selective polyethylene acts as a convection guard. The honeycomb might suppress counterproductive convective gains more, while still allowing radiant transfer. The scaffolding is omitted for clarity.

### Radiative cooling with two different infrared transparent insulations



**Figure 3.** With an intervention after 30 minutes, both plates (T2, T3) began to cool faster, nearing stagnation 5C below ambient temperature. The plate *without* the baffle cooled faster during this time; after 90 minutes, a fan was turned on, and it heated faster (see figure 2).

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Unexpectedly, the sample *without* the aluminium baffle cooled slightly quicker than the one with. It was thought that this might be because the air around the samples was relatively still, so both air spaces were able to stratify successfully, and the conduction through the aluminium became relatively counter-productive. It was thought that the baffle would perform better in windier conditions, since the cells would better suppress convection. To gauge whether this might be true, a fan was blown across both surfaces after 30 minutes, corresponding with a rise in ambient temperature in the graph. The sample without the baffle warmed slightly quicker, suggesting that convection between plate and surface was indeed greater. Both samples stagnated at around 4C below ambient temperature before the fan was turned off.

No firm conclusions can be made from the experiment. The conditions were too uncontrolled and *ad hoc* changes were made while it was happening. It does, however, suggest that significant radiative cooling did take place, and provides a basis for more developed indoor and outdoor tests, night and day, perhaps even in different climates. Several materials in various configurations are in mind [7]. It would be straightforward, for instance, to test the influence the infrared reflectivity of cells by comparing an aluminium honeycomb with a card honeycomb of the same dimensions. More advanced tests might include infrared fibre optics or the effect of reduced air pressure within whichever component.

### **3.0 Biodegradable concrete formwork**

Buro Happold and Brunel University are involved with other industrial partners in a government funded research project to find wider applications for biodegradable expanded starch foam [9, 10], which is enjoying some success in the packaging industry as an alternative to expanded polystyrene foam. Concrete formwork was seen as one possible entry point into construction.

Expanded polystyrene foam (EPS) is also used to form complex concrete building forms, and sometimes functional void networks. Wet concrete is poured over the foam, and, depending on the function of the void, it is either left in or flushed out with solvents. Other materials used for void-formers include cardboard, thin sheet metal and plastic [11].

Starch foam is very water-soluble. But it would make a good void-former if it was 'skinned' to protect it from wet concrete, as it could be easily flushed out with water once the concrete had cured. The skin could be a bio-film for instance; the principle is to block the pores. This might prove a better end-of-life scenario compared to EPS. Less certain is how it will compare in other life-cycle stages.

Voids in concrete can have multiple functions. One type of pre-cast concrete slab has an internal void-network which plays a structural and thermal role. The voids give greater stiffness for less weight, and create a passage way for cool night air to pass through and discharge the slab of heat accumulated during the day, thereby 'unlocking' the thermal mass in a building [12].

These concrete slabs are formed by extrusion, which places firm limits on the complexity of geometry achievable. Internal geometries such as a 'corkscrew' or louvered fins might give better heat transfer for the

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same pressure drop [13]. These could be formed with a starch foam product. Adding functions to a product by taking material away is clearly an attractive eco-design strategy. Figure 4 shows a hypothetical concrete slab that combines structural, thermal and acoustic functions through design of internal and external geometry.



**Figure 4.** A hypothetical concrete floor slab. The internal and external geometry increase the functional unit by improving structural, thermal and acoustic functions. Starch foam could be used to form complex concrete forms such as these.

### 3.2 Experiment

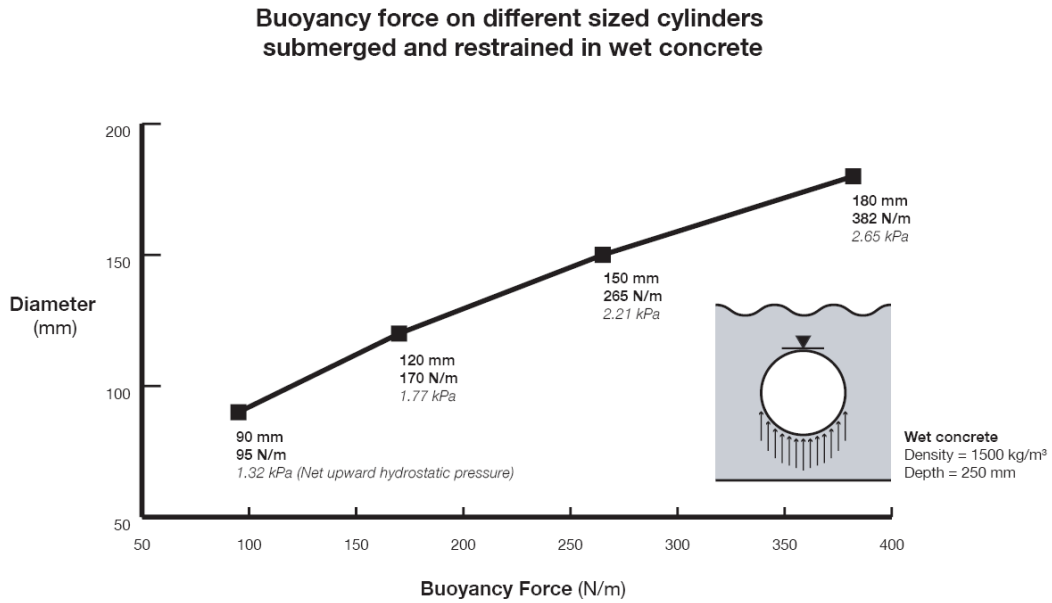
Void-formers float in wet concrete, and need to be restrained. Deformation will occur due to buoyancy forces; how tolerable the deformation will depend on the function of the void. Figure 5 shows the relationship between void-former diameter and upward buoyancy force in wet concrete of depth 250mm. It assumes the cylindrical void-former is restrained from above by the steel reinforcement grid. The greater the diameter, the more concrete is displaced, and the greater the buoyancy force. Equal and opposing horizontal hydrostatic pressures cancel one another.

An experiment was set-up to compare the vertical deflection of different starch foam cylinders under axial load. The aim was to see if the design loads in Figure 5 could be matched with acceptable deflections. Figure 6 shows the basic set up. The starch foam comes in the form of pultruded rods, brought together six-fold to form planks one rod high. These were converted into tubes by spiralling them round a pipe; the edges stick when moistened.

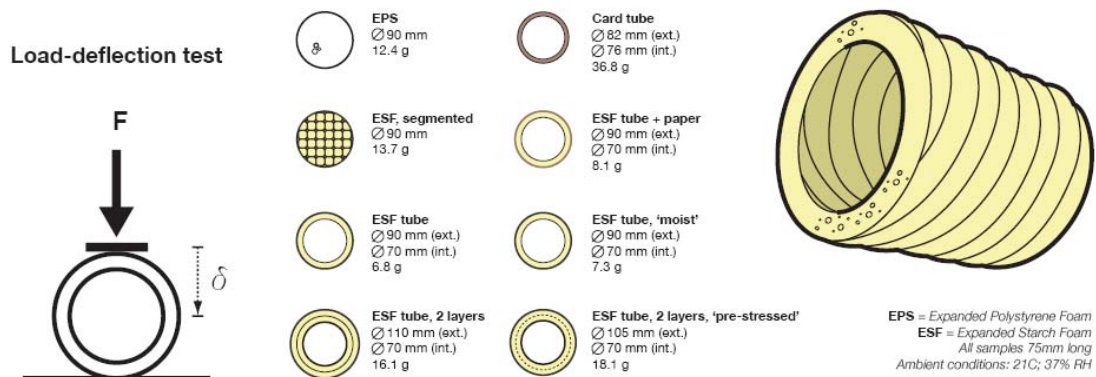
### 3.3 Results and discussion

Figure 7 shows the results of the experiment.

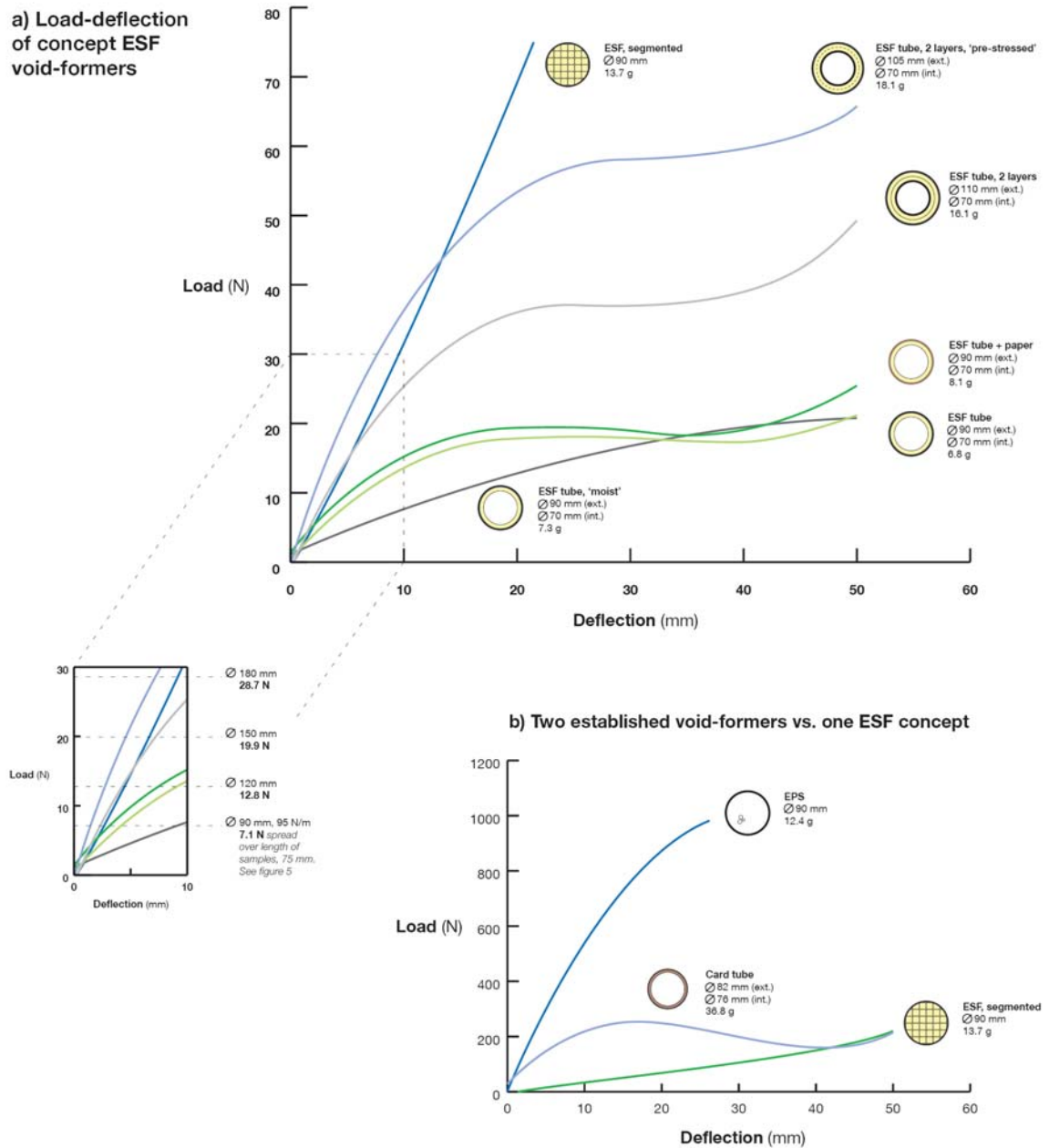
Foams usually exhibit a non-linear elastic stress-strain law [14]. None of the samples behaved this way – the plateaus on some of the curves show where failure occurred. We might have expected non-linear elastic behaviour with the segmented ESF sample. Presumably, the stiff pultruded walls of each segment stopped this from occurring.



**Figure 5.** Buoyancy force increases with diameter. The cylinder is restrained at the top by the steel reinforcement bars. Note that density of set reinforced concrete is 2400 kg/m<sup>3</sup>



**Figure 6.** Experimental set-up and samples prepared for testing. All samples were 75mm long. EPS and card tubes are used as void-formers in industry. The ESF comes in planks six segments wide: these were wrapped round a cylinder and cut to make tubes; the edges stick when moistened.



**Figure 7.** Load-deflection relationships for different void-formers (see figure 6). For similar weights, EPS is an order of magnitude stiffer than ESF (7.b). But this is excessive for the buoyancy design loads shown in figure 5 (insert of 7.a). ESF tubes use less material per diameter, and could be designed to meet acceptable deflections (7.a). Less water and pressure would be needed to flush tubes away, on account of their geometry and mass. Double layer tubes are stiffer if the two layers are joined *before* they are formed into tubes, rather than wrapped one after the other (7.a). This acts as a pre-stressing mechanism.

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For similar weights, an EPS cylinder is an order of magnitude stiffer than ESF cylinder made from stacked segmented planks. But this is excessive for the buoyancy design loads shown in figure 5, as is shown in the insert of figure 7.a, which assumes a worst case scenario where the buoyancy force is loaded uni-axially along the edge of the 75mm long samples. This is a promising eco-design result. Less EPS and card could be used to perform this particular function, and to compete, ESF would not need to be made denser than ESF.

Clearly, hollow tubes use less material per diameter than cylinders. Figure 7 suggests that ESF cylinders could be designed to deflect within acceptable bounds. As a further eco-design benefit, less water and pressure would be needed to flush tubes away, on account of their geometry and lower relative mass. Another finding is that double layer tubes are stiffer if the two layers are joined *before* they are formed into tubes, rather than wrapped one after the other. This acts as a pre-stressing mechanism. The results suggest that multi-layered tubes could be designed to make larger void-formers. Another important finding is that the moist tube was less stiff than the dry tube, but it did not fail. This emphasizes the importance of ‘skinning’ the product to provide a moisture barrier.

These preliminary results suggest that highly ‘flushable’ ESF tubes can be designed to deflect acceptably when submerged in wet concrete. There are several other dimensions to the void-former task however. Design for robustness is probably the next most important area of investigation.

#### **4.0 Design Method**

*TRIZ* is a Russian system of engineering problem solving, made up of several problem-framing and problem-solving tools. The acronym is usually translated into *Theory of Inventive Problem Solving*. One of the most popular tools is a look-up table made up of 39 opposing features (parameters, variables) of engineering systems such as strength, weight, speed, volume, temperature, ease of manufacture and versatility. The claim is that if you define your problem in its terms, the TRIZ contradiction matrix will point you to a handful of principles that have been found to resolve the trade-off. Altshuller and his colleagues reportedly found 40 such inventive principles from the study of 3 million patents [2].

More recently, a group of biologists made a condensed version of this matrix, rearranging the 39 features and 40 inventive principles into 6 meta-categories, or ‘operational fields’. These were Substance, Structure, Energy, Information, Space and Time [1]. This new 6x6 version of the TRIZ contradiction matrix was called PRIZM. A biological version of PRIZM was then constructed. The so-called ‘BioTRIZ’ matrix encapsulates 3000 of Evolution’s engineering strategies [1]. Vincent and his colleagues then compared the two 6x6 matrices, taking them as representative of innovation strategy in engineering and nature. There was only a 12% similarity. One of their conclusions was that human technology solves problems largely by manipulating the use of Energy, whereas biology uses Information and Structure – two factors largely ignored by technology.

The way BioTRIZ was applied to come up with the idea for infrared transparent insulation is described fully in [7]. The design conflict was defined as “The building mass should be allowed to reach thermal equilibrium with the sky (17 *Temperature*) without counterproductive energy inputs from the super system (22 *Loss of*

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Energy)” [17]. Both of these parameters fall into the meta-category ‘Energy’. The conflict ‘Energy’ vs. ‘Energy’ was then looked-up in the BioTRIZ matrix (see [1] and [15] matrix and definitions).

One of the strongest solutions offered by the BioTRIZ matrix was Inventive Principle (IP) 3, *Local Quality*, which, in short, suggests making the problematic object non-uniform. ‘Empty’ vertical pathways in the insulation would give the mass an infrared view of the sky. A honeycomb structure, for instance, might allow air to stagnate during radiation cooling to form an infrared transparent insulator. Alternatively, infrared fibre optics would let longwave radiation pass, and heat gain from the ambient would be purely from conduction.

Similarly, the idea of the ESF tube was based on IP 3, *Local Quality*. If you increase the density of the ESF block, you increase the stiffness, but at the cost of increased mass and decreased ‘flushability’. The idea to make tubes by wrapping the planks was based on IP 14 *Curvature*, while the IP 14 *Prestressing* inspired the better performing double layer tube. According to the PRIZM categories, *Local Quality* is Structural, *Curvature* is Spatial, and *Prestressing* is in the Energy category [15].

## Acknowledgement

The authors wish to acknowledge the assistance of Ali Ahmadnia, Hong Yeoh and Elmar Hess.

## References

- [1] Vincent JFV, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl A-K. Biomimetics: Its practice and theory. *J. R. Soc. Interface*, 2006, 3, 471–82. <http://journals.royalsociety.org/content/k048171720104k70/>
- [2] Altshuller G. The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity. Technical Innovation Center Inc, Worcester, MA, 1999
- [3] Bahadori M N. Passive Cooling Systems in Iranian Architecture, *Scientific American*, 1976
- [4] Yannas S, Erell E, Molina J L. *Roof Cooling Techniques: a Design Handbook*, Earthscan, London, 2006
- [5] Martin M. Radiative Cooling. In *Passive Cooling*, Cook J (ed), The MIT Press, London, 1989, 138 – 196
- [6] Granqvist C G, Hjortsberg A. Radiative cooling to low-temperatures – general considerations and application to selectively emitting SiO films. *Journal of Applied Physics*, 1981, 52: 4205-4220
- [7] Craig S, Harrison D, Cripps A & Knott D. BioTRIZ suggests radiative cooling of buildings can be done passively by changing the structure of the roof insulation to let longwave infrared pass. *Journal of Bionic Engineering*, March 2008 *In Press*
- [8] [www.kube.ch](http://www.kube.ch) (see figure 2 for product name)
- [9] Song, J. *Biodegradable Packaging Material*. Great Britain Patent Application, 2 352 230 A, Jan 2001
- [10] Song J, Wang Y, Gao Y, Almadnia A. Starch foams and composites for industrial applications. *Conference proceedings of Biofoams 2007, Capri 26-27th Sep*
- [11] The Concrete Society. *Formwork: a guide to good practice*. UK, 2nd ed. 1995
- [12] Barnard N. *Dynamic Energy Storage in the Building Fabric*, Technical Report 9/94, the Building Services Research and Information Association, Bracknell, 1995
- [13] Wadley, H N G. Multifunctional periodic cellular metals *Phil. Trans. R. Soc. A*. 364, 31-68, 15 Jan 2006
- [14] Ashby MF. The properties of foams and lattices. *Phil. Trans. R. Soc. A*. 364, 15-30, 15 Jan 2006
- [15] Vincent JFV, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl A-K. Appendices to Vincent *et al*: Biomimetics – its theory and practice. *Journal of the Royal Society Interface*, 2006, 3, 471–82. <http://journals.royalsociety.org/content/k048171720104k70/>