AUSTRALIAN MODERN BUILDING ALLIANCE

Safe and sustainable construction with polymers

Reference Paper 1:

Physical properties of polyurethane insulation

Introduction

Polyurethane (PUR) insulation is one of the most efficient thermal insulation materials, enabling effective energy savings with minimal thickness. This document describes the physical properties of PUR insulation, including the closely related polyisocyanurate (PIR) insulation.

Overview of polyurethane insulation

Polyurethane (PUR) insulation is a cellular polymer material (Figure 1) which is ideal for use in light-weight, low-energy or zero-energy (Passivhaus) buildings because of its low thermal conductivity, which minimises the thickness of building elements.

This document will discuss the properties of the most commonly used PUR products in the Australian building industry; polyisocyanurate (PIR) insulation board with flexible facings (Figure 2a), PIR metal faced sandwich panels (Figure 2b) and PUR spray foam (Figure 3).

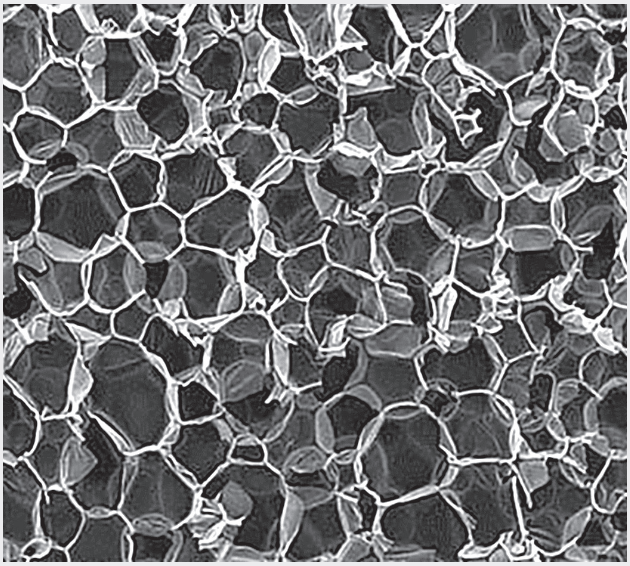

Figure 1: *Typical cellular structure of polyurethane insulation (photo courtesy of Covestro).*

Both PUR and PIR foam are manufactured from the same components, but PIR uses a different ratio of materials that results in the polyurethane structure having a higher cross-link density and stronger chemical bonds. As a result, PIR foam is more thermally stable at higher temperatures.

PIR insulation boards (Figure 2a) have a PIR foam core with flexible facings of mineral/glass fleece, aluminium foil or composite film, depending on the application of the boards. The most commonly available board in Australia has an aluminium foil facing which serves as a vapour-resistive barrier, air barrier and a weather (water)-resistive barrier and provides some protection against mechanical damage.

The boards are typically manufactured in sizes of 2400mm x 1200mm and can have different edge profiles such as tongue-and-groove, stepped or flat. They can also be manufactured with one of the flexible facings replaced with a rigid facing such as plasterboard which are used for retrofitting insulation in existing buildings. The relevant European standard for specification for PIR insulation boards used in buildings is BS EN 13165:2012.

PIR metal faced sandwich panels (Figure 2b) have a PIR foam core between two metal facers of steel or aluminium sheet. They are typically manufactured in widths of 1200mm and lengths up to 16m – the long edges of the panels usually have a tongue-and-groove profile and factory installed seals for rapid air-tight installation.

The self-supporting prefabricated construction elements are relatively low weight but have good strength, are easy to transport and can be installed with minimal labour. The relevant European standard for specifications for polyurethane sandwich panels is BS EN 14509:2013.

PUR spray foam (SPF) is sprayed onto a substrate on-site where it self-adheres and forms a seamless blanket of insulation which can be built to any desired thickness by multiple passes (Figure 3). There are two types of SPF; closed cell spray foam (ccSPF) and open celled spray foam (ocSPF). The relevant European SPF specification standard is BS EN 14315-1:2013.

Unlike most PUR insulation, ocSPF does not have a closed cellular structure so it has a thermal conductivity similar to fiberglass insulation (Table 1) but, unlike fiberglass insulation, at a minimum thickness of 90mm it is an air barrier (Table 5). In one study using identical houses constructed in Texas,[1] substituting fiberglass batts at the ceiling level (vented attic) with ocSPF at the roof deck level (unvented attic), followed by substituting loose-fill fiberglass in the walls, gave a reduction in measured building air leakage from ACH50 = 5.84 to 3.64 and 1.95 respectively, which afforded increased energy savings of 16 per cent and 22 per cent.

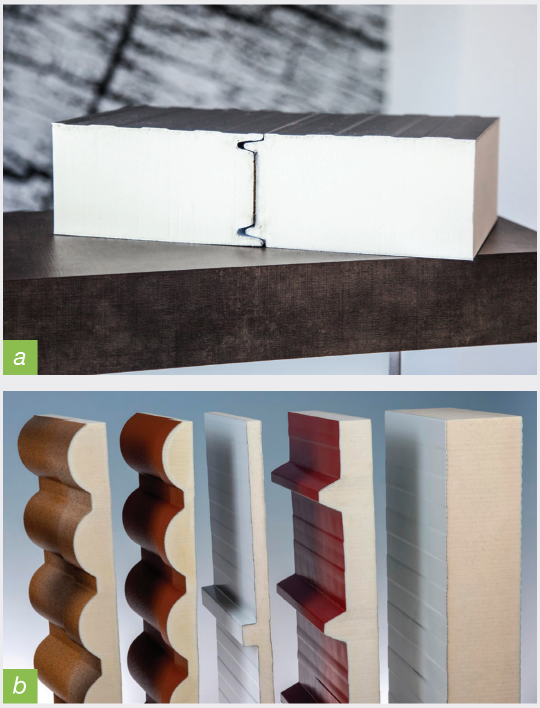

Figure 2: *(a) polyisocyanurate insulation board (photo courtesy of Huntsman International LLC), (b) polyurethane or polyisocyanurate sandwich panels (photo courtesy of Covestro).*

Figure 3: *Installation of polyurethane spray foam to a wall (photo courtesy of Huntsman International LLC).*

Physical properties of polyurethane insulation

When selecting suitable thermal insulation material, the required thermal properties are of prime importance. For the functionality and safety of the building, other important criteria in the choice of insulation are mechanical strength, resistance to ageing, resistance to air and moisture penetration and fire performance. PUR insulation has low thermal conductivity values to achieve optimal energy savings. The excellent mechanical strength values and exceptional durability of PUR insulation fulfil all the requirements of insulation materials used in the building industry.

Thermal conductivity of polyurethane insulation

PUR insulation has a very low *thermal conductivity* or a high *R-value* (Figure 4), which means that building elements, such as walls, can be thinner while still achieving a common insulation value – thereby either maximising internal space or decreasing the size of the building footprint.

The very low thermal conductivity of PUR insulation, aside from ocSPF, is largely the result of using blowing agents with thermal conductivities lower than that of air. After manufacture, the initial thermal conductivity ages due to the diffusion of CO_2 out of the foam and the diffusion of air into the foam, but after approximately three years the cell gas composition reaches a stable equilibrium. In Australia, the *aged thermal conductivity* of PUR insulation is measured according to AS/NZS 4859.1 and typical values for polyurethane insulation are summarised in Table 1.

***Figure 4:** Insulation thickness at equivalent R-value.*

Thermal conductivity (λ) is the heat flow in watts (W) through a 1m² surface and 1m thick flat layer of a material when the temperature difference between the two surfaces in the direction of heat flow amounts to 1 Kelvin (K). The unit of measurement is W/(m·K).

Thermal resistance (R) is the thermal insulation effect of a constructional layer. It is obtained by dividing the thickness (d) by the design thermal conductivity value of a building component: $R = d/\lambda$ (in accordance with EN ISO 6946). The unit of thermal resistance (R) is $(m^2 \cdot K)/W$. In building components comprising several layers, the thermal resistances of the individual layers are added together.

Thermal transmittance (U) is the heat flow in watts (W) through 1m² of a building component when the temperature difference between the surfaces in the direction of heat flow is 1K. $U = 1/R$ for a given construction and the unit of measurement is $W/(m^2 \cdot K)$.

Note: The XPS value reflects the transition from HFC blowing agents as in Europe.

Unlike expanded polystyrene (EPS),[2] the thermal conductivity of PUR insulation does not change significantly in the density range relevant for buildings. Similarly, unlike fiberglass batts and EPS,[2] water absorption has only a small impact on the performance of PUR insulation. Studies undertaken by the Forschungsinstitut für Wärmeschutz e. V. Munich have shown that the increase in thermal conductivity of PUR insulation board after 28 days of immersion in water is negligible at around 0.0018 W/(m·K).[3] This is why PUR insulation is the recommended insulation for flood prone areas by the Department for Environment, Food and Rural Affairs[4] and the Federal Emergency Management Agency[5] in the USA.

Material	PIR Insulation Board (foil)	PIR Sandwich Panels	ccSPF	ocSPF
Thermal conductivity W/(m·K)	0.021	0.022	0.022	0.038
R-value @ 50mm	2.38	2.27	2.27	1.32

***Table 1:** Typical declared product R-values for polyurethane insulation (AS/NZS 4859.1:2018 @ 23°C).*

Density of polyurethane insulation

The density of PUR insulation in buildings normally ranges between 8 to 35 kg/m³ (Table 2) because only a small portion of the PUR insulation consists of solid material (Figure 1). At a density of 30 kg/m³ – which is common in building applications – the solid polymer material makes up only three per cent of the volume. Obviously, facings such as steel significantly increase the weight of the insulation product.

Material	PIR Insulation Board (foil)	PIR Sandwich Panels	ccSPF	ocSPF
Apparent Density (kg/m³)	36-38 (core)	36-38 (core)	35	8
Weight (kg.m²) @ 50mm	1.8-1.9	11.2	1.75	0.40
Notes: The weight of the sandwich panel includes two steel facers of around 0.4 and 0.5mm (internal and external).				

***Table 2:** Typical weight of polyurethane insulation products.*

Compressive strength of polyurethane insulation

The compressive strength of PUR insulation is primarily a function of its density. When looking at material behaviour under load, we differentiate between compressive stress at 10 per cent deformation (σ_{10}) and compressive strength (σ_m) (Figure 5). The compressive strength of PUR is reported at 10 per cent deformation (σ_{10}) in the absence of catastrophic failure.

The σ_m and σ_{10} are measured in accordance with EN 826. These measured values can be employed to compare various insulation materials and for most PUR insulation applications, a compressive strength σ_m or compressive stress σ_{10} value of 100 kPa is sufficient.

Typical compressive strength values for PUR insulation are summarised in Table 3. Note that ocSPF is only used in non-load bearing applications such as between the studs in lightweight frame construction.

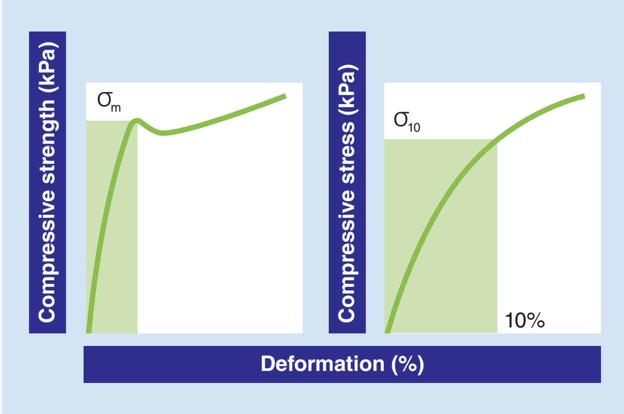

***Figure 5:** Compressive strength and compressive stress at 10 per cent deformation.*[3]

Material	PIR Insulation Board (foil)	PIR Sandwich Panels	ccSPF	ocSPF
Apparent Density (kg/m³)	36-38 (core)	36-38 (core)	35	8
Compressive strength (kPa) (typical)	120	120	150	< 5

***Table 3:** Typical compressive strength of PUR insulation products.*

However, in some applications like flooring where higher pressure loadings can occur due to machinery or stored materials, the deformation under continuous stress (σ_c) must not significantly exceed two per cent over a load period of 20 and 50 years respectively.

Continuous pressure tests in accordance with EN 1606 on PUR insulation board with aluminium facings and a density of 33 kg/m³ (Figure 6), subject to a continuous load of 40 kPa over a two-year and a five-year period, had only 1.4 per cent and 1.5 per cent deformation respectively. Using the Findley extrapolation procedure, deformation values of 1.7 per cent and 1.9 per cent were obtained for periods of continuous compressive stress of 20 years and 50 years respectively.[3]

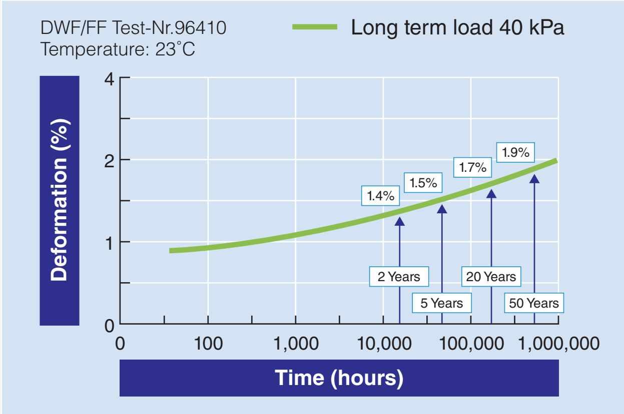

***Figure 6:** Long-term pressure curves at 40 kPa for PUR insulation board.*[3]

Tensile, shear and bending strength of polyurethane insulation

In some applications, PUR insulation can be exposed to tensile, shear and bending stresses. Thanks to their stability and exceptional insulation properties, composite elements with a rigid PUR foam core have a proven performance record – even in the case of extremely thin elements. If rigid PIR insulation board is used for thermal insulation in flat roofs, interior finishing, or in an external thermal insulation composite system (ETICS), it is important to ensure that the composite structure remains intact with no breaks in the insulation layer. Tensile stress and shear strength are important in this respect. Tensile stress perpendicular (σ_{mt}) to the faces is determined in accordance with EN 1607. Depending on the density, the values for PUR insulation lie between 40 to 900 kPa.

Depending on density, PUR insulation exhibits shear strengths in accordance with EN 12090 of between 120 and 450 kPa. The bending strength (σ_b) determined in accordance with EN 12089 describes the behaviour under bending stress in certain application areas, such as plaster supports in wooden structures, or bridging large open spans between the top chords in roofing constructions. The bending strength of composite elements with a rigid PUR foam core depends on the foam density and the facings used; the values lie between 250 and 1,300 kPa.

Polyurethane water absorption

Given the closed cell structure and/or facers, ccSPF, PIR board insulation (taped or sealed with one component foam),[6] and PIR sandwich panels (fitted with factory installed seals) are effective *water-resistive barriers*. Naked ccSPF only absorbs a maximum of 0.3 per cent water (by volume) when tested to ASTM D2842. Further, ccSPF is water resistant[6] under EN 12865:2001 for driving rain up to the maximum test pressure of 1800 Pa, which is equivalent to a wind speed of 197 kilometres per hour.

Finally, because of its closed cell structure, PUR board insulation does not absorb moisture from the air or wick water due to capillary action. Laboratory tests at the Forschungsinstitut für Wärmeschutz e.V. Munich[3] on mineral fleece faced PUR insulation boards immersed for 28 days in water (a worst case scenario due to the use of a fleece facing), in accordance with EN 12087, had an absorption level around 1.3 per cent by volume (Figure 7).

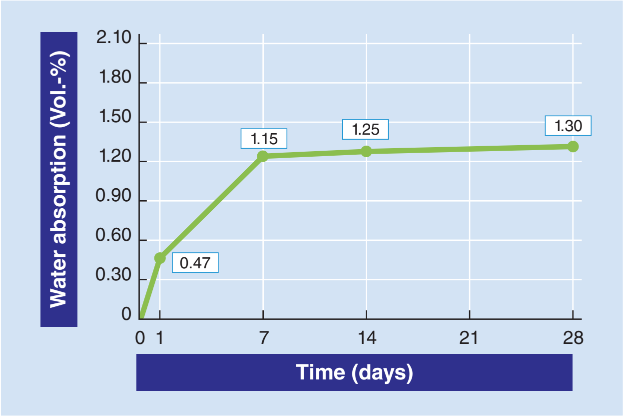

Figure 7: *Water absorption of rigid polyurethane foam (PUR/PIR) after 28-day immersion in water.*[3]

Water vapour permeability of polyurethane insulation

Typical water vapour permeability (or water vapour resistivity) values for PUR insulation are summarised in Table 4. In North America, PIR insulation board and PIR sandwich panels, due to the facers, are classified as impermeable (Class I vapour retarder), while ccSPF at 50mm thickness is classified as vapour semi-impermeable (Class II vapour retarder), and ocSPF at 130mm thickness is classified as vapour semi-permeable (Class III vapour retarder). According to AS/NZS 4200.1:2017 both PIR insulation boards and PIR sandwich panels are Class 1 vapour barriers, ccSPF is a Class 2 vapour barrier and ocSPF is Class 3 vapour permeable material.

Material	PIR Insulation Board (foil)	PIR Sandwich Panels	ccSPF	ocSPF
AS 2495.5:1993 = ASTM E96 (23C/50% RH)	< 0.01 µg/N.s	< 0.01 µg/N.s	0.0525 µg/N.s @ 25mm	0.326 µg/N.s @ 90mm
	< 0.1 US perms	<0.1 perms	0.92 US perms	5.70 US perms
USA Classification	Class I vapour retarders		Class II	Class III
AS/NZS 4200.1[7]	Class 1 vapour barrier		Class 2	Class 3
AS 2495.5:1993 uses ASTM E96 Method B wet cup @ 23°C and 50 per cent RH.				
Water vapour retarders as classified in the USA and Canada according to ASTM E96: ***vapour impermeable*** or Class I vapour retarder – considered a vapour barrier: ***vapour semi-impermeable*** or Class II vapour retarder: ***vapour semi-permeable*** or Class III vapour retarder: ***vapour permeable*** is not considered a vapour retarder:				**Perms** ≤ 0.1 ≤ 1.0 ≤ 10.0 ≥ 10.0
AS/NZS 4200.1: 2017 definitions are slightly different but similar: ***Class 1 vapour barrier:*** ***Class 2 vapour barrier:*** ***Class 3 vapour permeable:*** ***Class 4 vapour permeable:***				**Permeance (µg/N.s)** ≤ 0.0022 0.0022-0.1429 0.1429-1.1403 > 1.14403
Notes: vapour permeance (µg/N.s) = 1/vapour resistivity (MN.s/g) and 1 US perm = 0.0572135 µg/N.s (vapour permeance).				

Table 4: *Typical ASTM E96 (23°C & 50 per cent RH) results for polyurethane insulation.*

Air permeability of polyurethane insulation

Typical air permeability values for PUR insulation are summarised in Table 5. Given the facers and closed cell structure of ccSPF, PIR insulation board and PIR sandwich panels, it should not come as a surprise they are an air barrier. ocSPF is only considered an air barrier when installed at a minimum thickness of 90mm. While SPF can provide a completely seamless air barrier when installed in a building element, the performance of a building element incorporating either PIR board insulation or PIR sandwich panels depends on the effective treatment of the joints. While PIR sandwich panels come with factory installed seals, in the case of PIR board insulation they can be taped or sealed with foam-in-a-can.[8] It is much easier to make a lightweight framed residential building airtight with SPF (between the studs) or PIR board insulation (external to the studs) than by using a combination of fiberglass batts between the studs with a wall wrap. That is why the Californian Building Codes (California Title 24 2019) only require the use of a wall wrap in conjunction with fiberglass batts between the studs.

Material	PIR Insulation Board (foil)	PIR Sandwich Panels	ccSPF	ocSPF
ASTM E2178 or ASTM E283	Not applicable due to facings		< 0.02 L/s.m² @ 25mm	0.001 L/s.m² @ 90mm
Classification	Air barrier		Air barrier	Air barrier
Notes: A material is defined as an air barrier in the USA and Canada if the material air leakage is < 0.02 L/s/m² @ 75 Pa (roughly equivalent to that of drywall).				

Table 5: *Typical leakage rates of polyurethane insulation products according to ASTM E2178.*

Thermal expansion of polyurethane insulation

All materials expand under the effects of heat. The coefficient of thermal expansion expresses the material-specific thermal expansion per 1 Kelvin increase in temperature. In closed-cell foamed plastics, the gas pressure in the cell structure also influences expansion. The coefficient of thermal expansion of rigid PUR foam depends on density, facing, attachment (if any) of the insulation material to a building component layer and the selected temperature range.

Measurements taken on PUR insulation boards with flexible facings and densities of between 30 and 35 kg/m³ yielded coefficients of thermal expansion of between 3 and 7 x $10^{-5}\cdot K^{-1}$. For PUR insulation boards without facings (Figure 8) and with densities of between 30 and 60 kg/m³ the linear coefficient of thermal expansion lies between 5 and 8 x $10^{-5}\cdot K^{-1}$. The coefficient of thermal expansion of insulation boards of higher density without facings is around 5 x $10^{-5}\cdot K^{-1}$. These values apply to boards or cut sections/mouldings that are not attached to a substrate or are not tautly mounted.

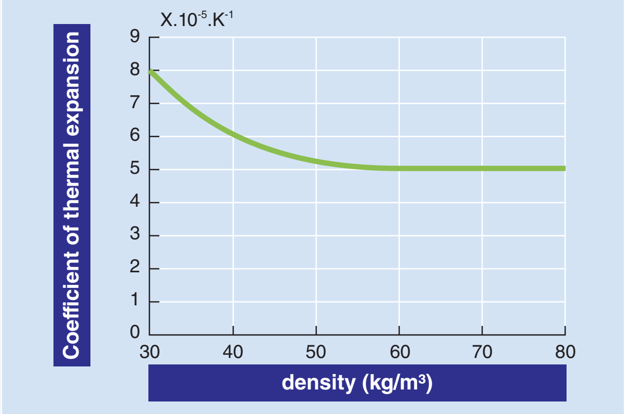

Figure 8: *Thermal expansion of rigid polyurethane foam (PUR/PIR) without facings. (Thermal expansion of rigid polyurethane foam (PUR/PIR) without facings in the temperature range -60°C to +20°C, measured in relation to density).[3]*

Specific heat capacity and heat storage of polyurethane insulation

The specific heat capacity (c_p) indicates how much heat energy is required to increase the temperature of 1 kg mass of a material by 1 Kelvin. Specific heat capacity c_p is measured in J/(kg·K). In accordance with EN 12524, these calculated values are to be used in special calculations of heat conduction in building components with unsteady boundary conditions.

The calculated value of specific heat capacity (c_p) of PUR insulation boards is 1,400-1,500 J/(kg·K). The heat storage capacity of building components is influenced by the specific heat capacity of the individual building materials they contain. The heat storage capacity C in J/(m²·K) specifies how much heat a homogeneous building material with a surface area of 1m² and thickness (t) can store when the temperature rises by 1 K. Heat storage capacity C in J/(m²·K) = specific heat capacity (c) x density (r) x thickness of the layer (t). PUR insulation board at a thickness of 105mm and a density of 30 kg/m³ has a heat storage capacity of 4.73 kJ/(m²·K).

Temperature stability of polyurethane insulation

Depending on the density and facings, PUR insulation materials for building applications can be used long-term over a temperature range of -30°C to +90°C. Further, they can withstand temperatures of up to 250°C for short periods with no adverse effects. PIR board insulation with mineral fleece facings is resistant to hot bitumen and can be used in flat roofing sealed with a bituminous roof covering.

Chemical, biological and UV stability of polyurethane foam

PUR insulation is resistant to most common chemical substances used in buildings. This includes most solvents used in adhesives, bituminous materials, wood protection products or sealing compounds. In addition, the insulation material is not susceptible to the effects of plasticisers used in sealing films, or to fuels, mineral oils, diluted acids and alkalis, exhaust gases or aggressive industrial atmospheres.

Further, PUR insulation does not rot; it resists mould and decay and is odour-neutral. UV radiation causes discolouring of the insulation without facings, or at the cut faces, and over time leads to a low-level sanding effect on the surface. However, this is not a technical drawback as the surface sanding can be removed in subsequent work steps.

Fire performance of polyurethane insulation

The Australian *reaction to fire* test is AS/NZS 1530.3 and the *fire resistance* test is AS 1530.4. Typical test results for PUR insulation to AS/NZ 1530.3 are summarised in Table 6 and compared with softwood to provide perspective. PIR insulation has a significantly lower flame spread compared to softwood.

Material	PIR Insulation Board (foil)	PIR Sandwich Panels	ccSPF	ocSPF	Australian Softwood
AS/NZS 1530.3	0,0,0,1	0,0,0,2	16,0,1,5	0,0,0,6	16,9,7,3

Note: Test results are for ignitibility, flame spread, heat release and smoke release
NTD = No test data

***Table 6:** Typical AS/NZS 1530.3 results for polyurethane insulation.*

Typical test results for PUR insulation to AS 1540.4 are summarised in Table 7. There are no fire resistance requirements in the Australian National Construction Code (NCC) 2019 for residential housing (Class 1 and 10a). PIR insulation board can be used in Type C walls in Class 2-9 buildings, but a performance solution is required for Type A and B walls.

Material		PIR Sandwich Panels	PIR Insulation Board (foil)
AS 1530.4	@ 80mm	-/60/28	No requirement for Class 1 & 10a buildings
	@ 100mm	-/132/28	Can be used for Fire Resisting Construction Type C walls in Class 2-9 buildings but a performance solution is required for Type A and B walls

***Table 7:** Typical AS 1530.4 results for polyurethane insulation.*

PIR insulation board and PIR sandwich panels test results under AS 5113 and AS 5637 are also summarised in Table 8. PIR insulation is different to EPS and XPS because it is a thermoset, which means it does not melt when exposed to heat. Further, PIR insulation chars when exposed to fire (preventing further spread) and self-extinguishes when the fire is removed. So, while PIR is combustible, it is also non-flammable. Because PIR board does not melt and drip in a fire, it can achieve an EW classification as part of an external insulated rainscreen system, in conjunction with a non-combustible rainscreen. PIR sandwich panels can also be used as a standalone insulated rainscreen system.

Material	PIR Insulation Board (foil faced)	PIR Sandwich Panels	ccSPF
AS 5113:2016 Classification	EW	EW	NTD
AS 5637:2015 Classification	Group 2	Group 2	Group 4
NTD = no test data			

***Table 8:** Typical AS 5113 and AS 5637 fire test results for polyurethane insulation.*

Finally, PIR sandwich panels are available with FM Global approved unlimited height and FM Global 4881 App 1 exterior wall system certifications.

Environmental performance and recycling of polyurethane insulation

Environmental product declarations to ISO standards are available for PIR insulation board, PIR sandwich panels and SPF. Polyurethanes are now manufactured with zero ozone depletion potential (ODP) and low global warming potential (GWP) blowing agents. In addition, all PUR insulation products contain recycled product to varying degrees. For example, PIR insulation board has a recycled content of around 10 per cent.

PUR insulation products are extremely durable. After dismantling/demolishing the building, undamaged PIR insulation boards can be re-used. Alternatively, clean PUR insulation waste can be crushed and pressed into boards similar to chipboard but with improved moisture resistance.

Other uses of the ground PUR insulation waste include use as oil binders or in combination with cement as insulating mortar. If the composition of the waste PUR insulation is known and there are no impurities, the raw materials can also be chemically recovered via glycolysis.

Finally, if the PUR insulation waste is contaminated with impurities, it can be burned together with other household waste in incineration plants with heat recovery systems, without causing any additional negative environmental impacts. Through this process, the energy in the insulation material is transformed into primary energy. This presents a dual energy saving: during the product's life it has saved up to 100 times the energy used in its manufacture, then it is used in a waste incineration plant with heat recovery systems – reducing the need for burning new energy sources such as oil or gas.

Conclusion

PUR insulation is one of the most efficient thermal insulation materials enabling effective energy savings with minimal thickness. Furthermore, it is highly durable – it does not sag or compact with use and is unaffected by moisture or air penetration, ensuring performance for the lifetime of the building.

The Forschungsinstitut für Wärmeschutz e. V. Munich has conducted tests on PIR insulation board sampled from a 30-year-old roof and found it to be in perfect condition in regards to the declared (aged) thermal conductivity, compressive strength, moisture content and reaction to fire.[9]

More information:
www.australianmodernbuildingalliance.org.au

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Acknowledgements

AMBA acknowledges that parts of this document have been reproduced with permission from PU Europe from their publication Thermal insulation materials made of polyurethane foam (PUR/PIR): Properties-Manufacture, Report No 1, October 2006.[3]

AMBA is an interest group within Chemistry Australia with a purpose to promote the safe and sustainable use of polymers in the built environment. AMBA membership includes the leading suppliers of polymer materials to Australia's building and construction industries.