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Modified wood: review of efficacy and service life testing

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Timber modification is an emerging commercial reality. Timber that has been acetylated, thermally modified or furfurylated is now readily available. However, the assessment of the effectiveness of each modification type in enhancement of durability, and therefore the effect on service life, has yet to be fully established. The paper includes a summary of the key points necessary to understand the mechanisms of protection given to wood by such modification. This paper also brings together the current work on the assessment of the durability of three types of modified wood and the effects that each has on the service life of timber structures, and addresses the harmonisation of standards in this field. This will allow for future development of appropriate standards for utilising these novel timber products, and therefore improve service life prediction and confidence when designing with these materials.

1. Introduction

Timber has been used in the manufacture of structures and shelters from the very earliest ages of man, and the excellent materials properties of timber are widely recognised. Projections made for the period through to the middle of the twenty-first century suggest that the worldwide demand for timber and timber products continues to grow. The rising demand for timber has led to the increase in plantation forestry and the use of fast-grown species and the development of technologies to improve the durability and mechanical properties of timbers. The improvement of timber properties has been undertaken in a variety of ways. This has included the design and manufacture of timber composites, which reduce the anisotropy and variability of timber and improve strength; the treatment of timber with toxic chemicals to prevent decay; and the use of non-toxic modifications to influence both the decay and the mechanical properties of the timber.

Wood preservation, or the treatment of timber with toxic chemicals to prevent decay, has been the mainstay of timber treatment since the 1830s. Various broad-range toxic chemicals have been used to prevent the decay of timber and these have been very successful in their application. Two of the most widely used preservatives within the past century have been creosote and chromated copper systems, including copper, chromium and arsenic (CCA) solutions. However, both systems are now covered by increased restriction through legislation in Europe and North America, with many other regions adopting similar legislation.

Within Europe, CCA is not supported under the biocidal products directive, and creosote can be used in restricted service environments away from public exposure. The raft of recent legislation has meant that in both markets, very few broad spectrum wood preservatives are available and performance of some of the newer formulations remains to be proven for use in class 4 applications (ground contact, as defined in BS EN 335 (BSI, 2013)). Various types of modified wood present options for use in use class 3 or use class 4 in place of preservative-treated wood.

Timber modification is a term given to a range of treatments that change the physical and/or chemical make-up of the timber to improve on one or more of the timber's properties.

Timber modification falls into two categories, the first being active modifications that react with or chemically change the timber (e.g. chemical modification, thermal treatments), second being passive modifications, which change the physical properties of the timber as a whole but do not change the chemical structure (e.g. impregnation treatments). Hill (2006) and Militz (2007) summarised the work of Norimoto and Gril (1993), which classified the types of modification by the effects that they have on the wood cell wall (Figures 1(a) and 1(b)).

A wide range of wood modification technologies exist (Figure 1(b)), some of which act to fill the cell lumena and others which fill the cell wall. Among these, some act by cross-linking, whether internal or by way of grafted bi-functional reagents, to form bridges between functional groups in the wood cell wall, thus restricting movement. Simple grafting reactions may also occur, bonding to hydroxyl groups or other functional groups in the cell wall, and modifications may include side reactions which can degrade the wood cell wall material either by heat or chemical action. The schematic diagram in Figure 1(b) generalises these processes for the main modification systems and a few emerging technologies, which are outside the scope of this review.

The majority of timber modifications are still in the development stages and have yet to produce significant amounts of commercially available modified timber; however, three processes have been successfully commercialised in the past two decades; acetylation (Accoya and Tricoya), thermal modification (including Thermowood, Platowood, Le Bois Perdure and Retiwood) and furfurylation (Kebony). Each of these modifications alters the timber in a characteristic and unique way. As these are products that are readily available in the market and relatively new to the design, architecture and engineering community, this review will consider these three modifications in detail, along with the effects that the modification has on the timber and how this influences selection for different applications.

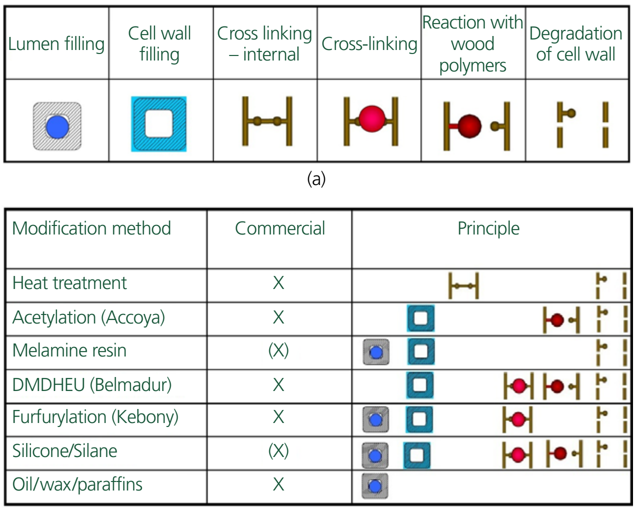

Figure 1. (a) Diagrams illustrating five types of wood modification which occur at a cellular level. (b) Summary of the combinations of modification process which occur together in each of the main wood modification technologies (adapted from Militz (2007))

2. Timber modification

2.1 Acetylation

The acetylation of timber is a chemical modification of the wood cell wall using acetic anhydride. The acetic anhydride molecules react with hydroxyl groups within the wood cell walls, grafting an acetate moiety into the wall. As a by-product, acetic acid is liberated and reclaimed by the treatment process (Figure 2).

The reaction of anhydrides with timber and the effects on the timber properties have been known for some time. Ridgeway and Wallington (1946) patented a method catalysed with zinc chloride and just a year later, Stamm and Tarkow (1947) patented a process for acetylating wood in the presence of pyridine. Several generations of research and commercial development have followed (as reviewed by Hill (2006)), meaning that the reactions today are undertaken in a more environmentally benign way, with little or no catalysts being used.

The reaction of the anhydride molecule with the hydroxyl group alters the effect of moisture on the timber; as the amount of substitution is increased, the wood's affinity for water decreases. Papadopoulos and Hill (2003) recorded changes in equilibrium moisture contents (the moisture content of the wood at equilibrium in an atmosphere with a given relative humidity and temperature) in acetylated pine under varying relative humidity (Table 1). Weight percent gain (WPG) is a commonly used measure for the level of modification, with 0% WPG seen as an untreated control (e.g. Table 1).

A reduction in equilibrium moisture content (EMC) is coupled with an increase in the anti-swelling efficiency (ASE), which quantifies the increase in the dimensional stability of the

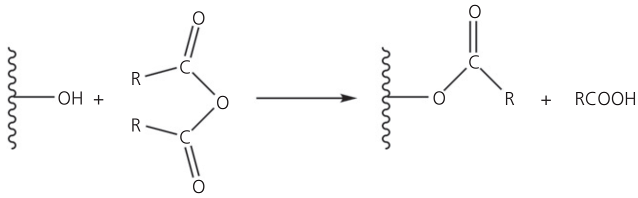

Figure 2. Anhydride modification of wood

Weight percent gain	Relative humidity (RH) 12%	23%	44%	55%	76%	93%
0·0	2·59	4·35	7·27	8·49	13·01	19·29
5·2	2·19	3·64	6·01	7·25	10·87	16·01
11·4	1·91	3·07	5·27	6·35	9·62	15·01
15·8	1·63	2·54	4·39	5·16	7·77	12·02
19·6	1·24	2·13	3·74	4·43	6·71	10·37
22·5	0·99	1·73	3·28	3·91	6·05	9·57

Table 1. Adapted from mean values for experimentally derived EMCs at various levels of RH for acetic anhydride modified Corsican pine (Papadopoulos and Hill, 2003)

timbers. These are both important factors when using timber in the built environment. Baird (1969) showed that as the WPG increases with anhydride modification, the ASE of white pine also increases. The volumetric swelling of cross-sections of the pine timber was reduced by up to 75% with acetic anhydride modification. These results are similar to the results from the work of Goethals and Stevens (1994) and Hill and Jones (1996).

The acetylation of timber and timber products also leads to an increase in the decay resistance of the products. Chow *et al.* (1994) acetylated aspen and southern pine chips for use in composite boards. The chips were acetylated to 23% WPG and then were pressure refined to a fibrous state. Boards were produced containing 3 and 7% phenol formaldehyde resin. The boards were then tested in accordance with ASTM method D2017 (ASTM, 1991) against both white and brown rot-causing fungi. It was found that the acetylation of the fibres prior to the production of the boards gave an increase in decay resistance to both the 3 and 7% resinated boards (Table 2).

Fungus	Wood Species	3% resin UT	3% resin T	7% resin UT	7% resin T
G. trabeum	Aspen	47·0	1·7	30·0	1·0
	S. pine	44·6	0·9	36·9	0·4
P. placenta	Aspen	50·8	1·1	40·8	1·1
	S. pine	50·0	2·5	34·3	2·5
P. versicolor	Aspen	80·0	2·2	60·9	2·9
	S. pine	18·1	2·3	21·3	2·2

Table 2. Average weight loss for composite boards made with anhydride modified fibres (T) and control fibres (UT) (adapted from Chow *et al.* (1994))

Peterson and Thomas (1978) modified small blocks (10 mm × 10 mm × 5 mm) of yellow poplar, loblolly pine and green ash for 1, 5 and 29 h. The sterilised blocks were transferred into soil bins inoculated with a brown (*Gloeophyllum trabeum*) or white (*Coriolus versicolor*) rot-causing fungus and stored at 25°C and 70% relative humidity (RH) for a period of 6 weeks (in accordance with AWPA M10-74 (AWPA, 1974)) (Table 3).

These tests (Peterson and Thomas, 1978) showed that the protection from fungal decay was not due to any fungitoxic nature of the anhydride. They noted that the fungus grew out of the wood onto the agar on the culture plates. This conclusion was further developed by Suttie *et al.* (1997) who noted that the bio-resistance must be, at least in part, due to the lower moisture content of chemically modified wood. Suttie *et al.* modified blocks with acetic, propionic, butyric, hexanoic and succinic anhydrides, and found that there is no consistent trend to indicate an advantage in using one anhydride over another. However, it was indicated that anhydrides with smaller molecule size gave a better final product than the larger anhydride molecules.

The effect of acetylation on the mechanical properties of wood is two-fold and competing (Hill, 2006). First, the reduction in the equilibrium moisture content leads to an increase in the modulus of elasticity (MOE), modulus of rupture (MOR) and tensile strength of the timber, as would be expected from a reduction in EMC, even in untreated wood. However, the degradation of the cell wall due to the heat used in the treatment process and the evolution of acetic acid coupled with the reduction in fibre number per unit area, leads to a potential drop in properties. Both of these factors are governed by the time and temperature of the reaction, which through economic necessity has been driven down. Much of the data on changes in mechanical properties of acetylated timber are inconclusive and do not show a clear trend. As early as 1946, Tarkow *et al.* reported that although changes in mechanical properties in two different species were not significant, they did show that

Treatment	Weight loss: % *G. trabeum* Poplar	*G. trabeum* Ash	*G. trabeum* Pine	*C. versicolor* Poplar	*C. versicolor* Ash	*C. versicolor* Pine
Control	66·8	63·7	61·0	33·6	40·8	28·0
1 h	10·3	3·7	6·7	3·3	7·9	1·6
5 h	2·6	2·4	2·6	3·1	6·6	1·4
29 h	1·6	1·4	1·7	2·9	6·0	1·1

Table 3. Average weight losses for brown rotted and white rotted acetylated wood (adapted from Peterson and Thomas (1978))

there was a variation between species, with Sitka spruce showing an increase in strength up to a substitution level of 20%, whereas yellow birch showed a decrease in properties at 16% WPG (Tarkow *et al.*, 1946). Larsson and Simonson (1994) reported that, following acetylation, the MOR and MOE of pine was reduced by 6% for Scots pine but increased by 7% for Norway spruce.

On a larger scale, Bongers and Beckers (2003) undertook a comprehensive study of mechanical properties of acetylated timbers: beech, poplar, Scots pine and radiata pine. They modified the timbers in 4 m lengths and determined MOE, MOR, impact resistance, hardness, shear strength, resistance to screw withdrawal and compression parallel to the grain. As with previous studies, variable results were obtained, with some species showing an increase in properties and others showing a decrease. However, it was noted that the variation in the data within species was low. As a result, the best approach is to seek engineering values for the strength or other mechanical properties of a given species of acetylated timber direct from the supplier. For example, Accoya is available in softwood (radiata pine) and hardwood (acetylated alder) products.

Acetic anhydride modified timber has been commercialised by Accsys Technologies and is currently available under the trademarks Accoya (for solid wood) and Tricoya (for panel products). In March 2014, Accsys Technologies reported a total annual production of 25 391 m^3 and sales within the UK alone grew by 93% (Accsys Technologies, 2014a). Accsys Technologies also license the technology for acetylation of timber worldwide and currently have enabled several large-scale producers to operate.

2.2 Thermal modification

Unlike acetylation, thermal modification (sometimes referred to as 'heat treatment') covers a wide range of products and treatment methods and, of the modification techniques, is the most advanced commercially. Production by Thermowood was already over 18 799 m^3 in 2001, and Platowood was also commercially available at this time (Esteves and Pereira, 2009). Many different methods are now covered by patents, and the products are traded under names such as Thermowood, Platowood, Retiwood and Le Bois Perdure.

In general the thermal treatment process involves exposing the timber to an increase in temperature up to a treatment temperature of between 180°C and 260°C. Higher temperatures are known to lead to a more severe degradation of the material. The process is selected to optimise the level of thermally induced changes in the wood while retaining an acceptable level of strength or other properties. There has been a renewed interest in the milder treatments of timber; these have been used primarily for aesthetic and dimensional stability reasons rather than altering the durability and mechanical properties of the timber (Spear *et al.*, 2014).

The processes used for thermal modification vary greatly between the differing systems; however, Hill (2006) lists the important processing variables that will have an effect on the end properties of the timber.

- Time and temperature of the treatment: the increase in temperature of the wood will be correlated with moisture and volatiles being driven off from the timber, then as the temperature continues to rise, changes in the cell wall chemistry occur and a change in colour begins to be evident. When temperatures reach the higher end of the thermal treatment scale the changes affect the cell wall components and introduce potential strength loss.
- The atmosphere under which the treatment takes place: the treatment of timber can take place under vacuum, in air or in an inert atmosphere. The atmosphere will have an effect on the type of chemical changes that occur; for example, oxidative reactions occur in oxygen-rich environments and not in others.
- A closed as opposed to an open system: the use of a closed system will allow the build-up of degradation products such as acetic acid within the system and these in turn can accelerate the rate of reaction and of any degradation side effects on the timber (Stamm, 1956). An additional difference between a closed system and an open system is that if the timber is not dry when the treatment is started, steam will form within the system. As the steam forms, a pressure can build up within the system, changing the reaction characteristics.
- The species of wood: the reaction of different species to treatment will differ between the species. This is most notable when comparing hardwoods and softwoods under the same treatment conditions, due to differences in the composition of hemicellulose and lignin between these two groups (Militz, 2002). In addition, the wood anatomical differences among hardwoods or between hardwoods and softwoods can influence processing factors and mechanical properties of the treated wood.
- Whether the treatments are wet or dry process: timber can be treated in a dry atmosphere, or a high-water-vapour atmosphere, and systems may be referred to thermal or hygrothermal. Within a hygrothermal system the steam acts as a heat transfer medium and additionally as an inert blanket to limit oxidation.
- The dimensions of the samples: the rate of thermal transfer is a very significant factor in the development of a heat treatment process. The dimensions of the timbers to be treated will therefore require subtle alteration to the schedule to maintain the homogeneity of the treatments.

Thermal modification of timbers can lead to various changes in the physical and mechanical properties of the timber, as follows

- a mass loss of the timber
- an improvement in the dimensional stability of the timber
- a reduction in the equilibrium moisture content of the timber
- an improvement in the decay resistance of the timber
- there is generally an increase in modulus with mild treatments, which then reduces as the treatments become more intense
- there is generally a reduction in impact toughness and MOR for the more intense treatments
- a reduced abrasion resistance
- a tendency to crack and split; in softwood species the knots may become loose and can fall out of the timber
- the colour of the timber darkens.

The changes mentioned above can be controlled by the type and severity of the thermal treatment. When comparing the thermal treatments against each other or a standard specification it is vital that the process parameters are known and that these are taken in to account with any comparison. A large amount of laboratory data has been published in research journals; however, for the engineer, published values relating to the intended product should be compared. Each of the commercial systems has developed clearly identifiable grades or products for well-defined applications; for example, Thermowood-S (Thermo-S) for applications requiring enhanced stability, and Thermowood-D (Thermo-D) for applications requiring durability. Note that each classification of product will behave in a characteristic manner, and data for Thermo-D will not be applicable as a substitute for Thermo-S or for Platowood, and vice versa owing to the designed-in differences in performance.

The loss of mass of the timber is often used as an indication of treatment intensity, and therefore the level of stability or durability properties achieved. Figure 3 shows how the mass loss of timber evolves over time at different temperatures. Again it must be pointed out that, although there is a lot of data in the scientific literature on mass loss in the thermal treatment process, it is difficult to compare as the treatment regimes, the species and the starting moisture contents differ (Esteves and Pereira, 2009).

The change in colour of the timber towards a darker brown is related to the type, duration and temperature of the treatments. The longer the treatment and the higher the temperature the deeper the resultant colour; however, treatment under a nitrogen atmosphere will result in a lighter colour when compared to a similar treatment in air. An understanding of the process parameters and the effects of colour change has led some

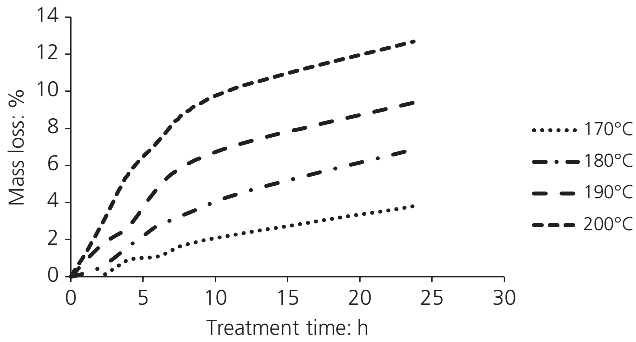

Figure 3. Wood mass loss plotted against heating time for different temperatures (source: Esteves and Pereira (2009), adapted from results in Esteves *et al.* (2008b))

researchers to using colour change as a quality control indicator and using it to predict performance in service (Bekhta and Niemz, 2003; Bourgois *et al.*, 1991; Spear *et al.*, 2014).

Thermal modification generally decreases the EMC of timber; however, it is again difficult to compare research due to differing process parameters. Esteves *et al.* (2007a, 2007b) report that the reduction in the EMC of the timber only occurs between mass losses of 4 and 6% and then the EMC reaches a minimum value. The reduction in the EMC within timbers has been reported to be due to a number of factors: Jämsä and Viitaniemi (2001) reported that there were fewer hydroxyl groups within the treated timber due to the chemical changes that occur predominantly in the hemicelluloses during thermal modification. Other authors have suggested that the reduction in EMC and accessible hydroxyl groups is due to the increase in cellulose crystallinity (Bhuiyan and Hirai, 2005; Boonstra and Tjeerdsma, 2006) as well as the cross-linking reactions of lignin (Boonstra and Tjeerdsma, 2006; Esteves *et al.*, 2008a, 2008b; Tjeerdsma and Militz, 2005). Thermo-S is reported to have an equilibrium moisture content of 6–7% for spruce and 6–8% for pine, when at 65% RH (Stora Enso, 2014). Under the equivalent conditions untreated timber would be at 12–13% moisture content.

The reduction in the EMC leads to an increase in dimensional stability, in the same manner that occurs in acetylated timber. Burmester (1973) reported that it was possible, with optimal pressure and temperature, to reduce the swelling of oak by 75%, beech by 60%, pine by 55% and spruce by 52%. Dirol and Guyonnet (1993) reported that the radial and tangential swelling was reduced more than the longitudinal swelling and the reduction increased as the severity of the treatments increased. Seborg *et al.* (1953) reported that the anti-swelling efficiency was dependent on the atmosphere in which the modification had taken place. Wood samples treated in air or nitrogen at 300°C reached a maximum dimensional stability with 20% weight loss; beyond this, dimensional stability was only increased by the use of an open system in nitrogen.

The thermal treatment of timbers can lead to a reduction in the surface energy of the timber and thus a decrease in the wettability of the timber. This will lead to a decrease in the bondability of the timber. This has been shown to be the case with phenol formaldehyde resins (Chow, 1971), urea formaldehyde resins (Chang and Keith, 1978) and polyvinyl acetate (PVA) adhesives (Bengtsson *et al.*, 2003). Generally the advice given for gluing or laminating thermally treated wood is to increase the time between glue application and joint closure to allow the adhesive moisture to migrate sufficiently into the drier timber. For PVA adhesives, better results are obtained when working with a formulation which has a lower moisture content, and drying time may need to be extended. Specific details are available from the suppliers for the thermal modification systems.

As mentioned above, thermal modification of timber will confer a degree of enhanced decay resistance to the timber. As with all properties, the decay resistance of heat-treated wood is dependent on many factors, including the species, temperature, duration and type of treatment. Although the mechanisms for decay resistance have yet to be established, they are undoubtedly related to the loss of polysaccharides, the reduction in hydroxyl groups within the cell wall and the reduction in moisture content (Hill, 2006). It has also been suggested that biocidal chemicals are formed within the timber during the thermal modification process, or that autocondensation of lignin and formation of furans from hemicellulose may inhibit microbial colonisation (Tjeerdsma *et al.*, 1998).

Much work has been undertaken to assess the decay resistance of heat-treated wood in pure culture tests. Kim *et al.* (1998) tested radiata pine from thermal treatments of 6 to 96 h, and used the data to predict that a treatment regime of 150°C for 150 h would give a comparable decay resistance to a 1% retention of a CCA preservative. For a higher treatment temperature of 180°C, the required treatment time for this level of performance was only 35 h. This is a consistently reported trend, that higher treatment intensities are required for suitable decay resistance, and that this can be achieved by increasing temperature above 200°C and by extending the treatment duration. Data from field trials and long-term testing is significantly less available (Alfredsen and Westin, 2009). However, all researchers who have undertaken field trials have suggested that thermally modified timber was only suitable for applications out of ground contact (use classes 1, 2 and 3 under BS EN 335 (BSI, 2013)).

Colour stability of natural wood in natural light has been an issue with some species, and it has been found that the colour stability of thermally modified wood is better than the untreated counterpart. For example, Ayadi *et al.* (2003) showed that darkening of ash, beech, pine and poplar wood was lower for retified wood than untreated samples in artificial weathering tests which cycled ultraviolet light with condensation. When rainfall is included in the artificial weathering system, the colour change of untreated and thermally treated soft and hardwoods progresses toward a lighter rather than darker colour due to the leaching of lignin degradation products formed by photo-oxidative processes on the wood surface (Syriänen and Kangas, 2000). It is reported that thermally treated wood will weather at a similar rate to that expected for western red cedar or larch, possibly in one summer if placed on a south-facing wall (Stora Enso, 2014). The lignin content of thermally treated softwoods remains higher than untreated timbers; however, Nuopponen *et al.* (2004) reported that the phenolic content of Thermowood remained high after a 7-year weathering exposure, unlike untreated wood, which was predominantly cellulosic. It is thought that the additional cross-linking which occurs in lignin, and the linking to hemicellulose degradation products, may retard the leaching process.

Accelerated weathering tests (in the laboratory) have shown beneficial effects for thermally treated Jack pine (from the Perdure process) when it is coated or stained; however, field tests over 5 years using Thermowood showed that thermally treated timber requires a paint coating in order to prevent colonisation by stain fungi. The same trials indicated that various transparent wood stains did not prevent stain development in the thermally modified wood, whereas translucent coatings did (Ahola *et al.*, 2002). In the results of an 8-year exposure comparing acetylated, thermally treated and furfurylated softwoods, thermally treated pine and spruce performed well in resisting cracking, as did acetylated pine, while the acetylated pine showed the least flaking of the various coatings tested (Gobakken and Westin, 2012).

Thermal modification of timber has been commercialised throughout the world, and the larger of the companies trade on an international scale. Thermowood is a trademark that is used by various companies to market their modified timber. The timber has to be modified according to Thermowood specifications, and only members of the International Thermowood Association have the right to use the name. The Thermowood system includes two types of modified timber, Thermo-S and Thermo-D, intended for different applications. Thermo-S offers stability, whereas Thermo-D offers stability and durability. The company literature suggests that the swelling and shrinkage of the Thermo-S is between 6 and 8% and the timber is sufficiently durable for use in use class 1, 2 or 3·1 applications (Table 7), such as door and window components, fixtures in dry conditions, sauna benches, or garden furniture (International Thermowood Association, 2014).

Thermo-D is the more durable Thermowood product; it is produced at a higher temperature, that is, under a more intense modification regime, which reportedly gives higher stability, lower EMC (5–7%) and a darker colour. Most importantly Thermo-D achieves natural durability class 2 (see Table 6 later), making it suitable for a wider range of exterior applications, including cladding and exterior doors, which are used in class 3·2 situations. However, it is still not suitable for ground contact applications (use class 4).

Platowood (2014) supply heat-treated European softwood and the tropical hardwood Fraké. The treatment is a two-stage hygrothermal modification process at relatively mild conditions. This process, which leaves a higher cellulose content in the wood, is reported to lead to reduced losses of strength or toughness compared to other treatments. In 2001, Platowood began to supply modified timber and now supplies a variety of products including flooring, cladding, decking beams and rough sawn timber. It is reported to have a durability class of 1, and product information for use in class 3 and 4 applications is available from the company (Plato, 2010a, 2010b).

Le Bois Retifie is produced under a nitrogen atmosphere to inhibit strength loss. It has been industrialised in France since 1997, and is currently sold under the name Retiwood. The rights for a second French thermal modification technology, the Perdure process, were sold to PCI Industries (a Canadian company) in 2000, and production of Perdure wood started in 2003 at two locations in Quebec; further capacity at a third site was built in 2005 (Esteves and Pereira, 2009). Basic data comparing the processes and properties of the various thermally modified timbers has been compiled in Table 4.

2.3 Furfurylation

Unlike the two previous modifications that can be classified as active modifications, or modifications that affect the cell wall, furfurylation is a passive modification. Furfuryl alcohol (FA) is produced from a bio-based resource (usually corn cobs) and the solution is impregnated into the wood, where it polymerises in the wood voids and the lumen. The polymerisation results in the formation of a three-dimensional network that extends from the lumen into the cell wall.

The treatment of wood with furfuryl alcohol has been reported as early as 1955 (Goldstein, 1955). The timber was treated with FA and a catalyst and heated to around 100°C. The ASE values for FA-impregnated woods with a range of catalysts (formic acid, citric acid, zinc chloride) ranged from 65 to 75%. In the initial work it was noted that the ASE was not great and this was due to the resin molecules being too large to penetrate the wood cell wall. Later FA solutions with storage catalysts were developed, which facilitated longer shelf life before the FA polymerised, and better permeation into a wide range of woods (Goldstein and Dreher, 1960).

The MOR, abrasion resistance and toughness are decreased while the MOE showed an increase (Goldstein, 1955). This was attributed to the degradation of the timber due to the acidic nature of the treatment. In more recent work, the catalysis of FA polymerisation can use cyclic carboxylic acid anhydrides (Schneider, 2002; Westin, 2004). The modern product can have WPGs from 20 to 125%, and properties such as hardness vary accordingly, being higher at high WPGs (Lande *et al.*, 2004). Stiffness stabilisation efficiency was reported in this study, where the dynamic MOE of samples tested in a humid (90% RH) and a dry (30% RH) climate were compared.

		Altered property			
Brand	Temperature range: °C	Colour	Stability	Durability	Weathering
Thermowood-S	185	✓	✓	✗	✓
Thermowood-D	215	✓	✓	✓	✓
Perdure	230	✓	✓	✓	
Retiwood	240	✓	✓	✓ insect ✓ fungi	✓
Platowood	Up to 190	✓	✓	✓	
Research work	120 to 260+	✓	✓	✓ or ✗	✓

Note: ✓ indicates increase or improvement; ✗ indicates no increase or improvement.

Table 4. Typical treatment details and reported property enhancement for the main commercially available thermally modified woods

	Joinery	Cladding	Decking	Garden furniture	Flooring	Interior furniture	Glulam	Canal linings	Posts	Bridges	Boat decks	Marine applications
Thermowood-S	✓	✓	✓	✓	✓	✓	✓					
Thermowood-D	✓	✓	✓	✓	✓	✓	✓					
Platowood		✓	✓					✓	✓			
Flo.Termo					✓						✓	
Celloc		✓							✓			
Lunawood	✓	✓	✓	✓	✓	✓	✓					
Other modified woods												
Accoya	✓	✓	✓	✓	✓		✓	✓	✓	✓		
Kebony		✓	✓	✓							✓	✓
Indurawood					✓	✓						
Vecowood					✓	✓						

Table 5. Possible end uses for commercial thermally treated woods, and some alternative modified wood products (source: TRADA (2010)). Accoya is acetylated, Kebony is furfurylated, Indurawood and Vecowood are impregnation modified)

It was shown that, at high WPG levels, the difference in stiffness was lowest, indicating a suitability for use in climates where a wide range of humidity is expected.

The decay resistance of FA-treated timber has been reported to improve in pure culture tests and in long-term field trials (Lande *et al.*, 2004). At high WPG (120–128%), weight loss in pure culture tests was lower than the CCA-treated control samples. Similarly, in high WPG samples, durability in field tests was as good as or better than CCA-treated timber. Studies with termites and marine borers also gave positive results.

The treatability of Scots pine sapwood was addressed in papers by Zimmer *et al.* (2008) and Larnøy *et al.* (2008). It was concluded in both papers that, although Scots pine is ranked as class 1 (easy to treat, according to BS EN 350-2 (BSI, 1994b)), there is a large variation in the uptake of FA by the timber, both from different stems and throughout a stem, and this needs to be taken into account when treating timber.

The colour change of furfurylated timber is distinctive and at high concentrations timber can appear to be almost black in colour, whereas at lower concentrations, softwood can move from a white colour to dark tropical hardwood appearance. Furfurylation has been commercialised as the Kebony process and is marketed for cladding, decking, boat decking and indoor applications (e.g. furniture).

2.4 Key themes

As can be seen, all three modification systems addressed in this review alter the affinity of the wood for moisture, and in a variety of ways, this reduces the level of moisture movement seen in service. This can have benefits in many respects – a reduced swelling of joinery gives not only lower chance of windows or door frames sticking in poor weather, but paint films may be under less strain, leading to a longer service life. The products differ in the extent of the modification, and the level of durability conferred; for example, thermally treated wood is not likely to be suitable for ground contact applications, whereas, with the correct level of modification, both acetylated and furfurylated timber can perform exceptionally well.

A simple indication of the products and their potential uses was published by TRADA in their *Wood Information Sheet* (TRADA, 2010) on modified wood products (Table 5).

3. Current standards for timber products and their applicability to modified timber

The catalogue of current standards influencing the use of timber and timber products within Europe is vast. The standards

Durability class	Class 1 – very durable	Class 2 – durable	Class 3 – moderately durable	Class 4 – slightly durable	Class 5 – not durable
Expected service life in ground contact (temperate)	25 years or more	15–25 years	10–15 years	5–10 years	Less than 5 years

Table 6. European durability classes (adapted from BS EN 350-1:1994 (BSI, 1994a)

Use class	Environmental conditions	Wood moisture	Type of attack
1	Indoor protected from weather and wetting	Below 20%	Insect attack only
2	Indoor with occasional wetting or humidity	Occasionally above 20%	Insect and moulds
3·1	Exterior above ground. Limited wetting	Frequently above 20%	Brown and white rot, soft rot, insect
3·2	Exterior above ground. Exposed to weather and frequent wetting	Frequently above 20%	Brown and white rot, soft rot, insect
4	Ground contact or fresh water contact	Permanently above 20%	Soft rot, brown and white rot
5	Salt water contact	Permanently above 20%	Marine borers

Table 7. Use class system under BS EN 335:2013 (BSI, 2013)

range from building regulations and codes (e.g. Eurocode 5 (BSI, 2004c)) to standard laboratory procedures; for example, the measurement of the moisture content of timber. All aspects of the use of timber are covered by the standards; however, new and novel products are not always treated specifically.

Currently there are few specific European standards for modified wood, and the products and their properties are tested to and defined by standards written to assess untreated timber or the properties conferred by traditional preservative treatments. Even for thermally modified timber, where DD CEN/TS 15679:2007 (BSI, 2007) sets out criteria for data to be supplied by manufacturers relating to their product, the test methods used are specified in existing standards. Although the use of current standards is in some cases reasonable and straightforward, in other cases the tests are not applicable either through the test protocol or through the assumptions made in the analysis and the interpretation of the data. Subtle adaptations of standard methods are commonly acknowledged as appropriate in research activities on modified wood, but no formal statement to ratify or specify these amendments, and the cases in which to apply them, has been made.

3.1 Durability testing

The durability of wood is a key property when assessing the use of timber in many construction or cladding roles, as decay by microorganisms can lead to failure of the timber. Different wood species (Evans *et al.*, 2008; Scheffer and Morrell, 1998), and indeed the same species grown under different conditions (Gambetta *et al.*, 2004), can have different levels of natural durability. In Europe, the natural durability of timber is classified by the five-level scheme in BS EN 350-1 (BSI, 1994a), as shown in Table 6. It is important to remember that the durability class is based on the durability of the heartwood rather than the sapwood, which is generally less durable.

Although a wide range of organisms can grow on or affect timber, the predominant risk to wood in service above ground is basidiomycete decay fungi. These fungi generally cause two distinct types of decay – brown or white rot – terms based on the characteristics of the decayed wood. These fungi require certain conditions for growth, with one very important criterion being the moisture content of the wood. A general rule is that dry wood is not susceptible to decay, with the threshold being 18–20% wood moisture content. If the wood is kept below this threshold then decay should not occur. However, this is not always possible and has led to a use class system, as shown in Table 7 (derived from EN 335 (BSI, 2013)).

Using these two classification systems together, the types of wood suitable for specific conditions can be decided. This is also used (BS EN 460 (BSI, 1994c)) to determine whether any preservative treatment is required; for example, in use class 1 preservative treatment is not required, however, in use class 3, timber of durability classes 3–5 may need to be treated with preservative.

Wood and wood products can be assessed to determine their natural or inherent durability using two major approaches.

- Outdoor service tests: samples are exposed outdoors for both above-ground and in-ground contact (use class 3 and 4), for example, BS EN 252 (BSI, 2012).
- Accelerated laboratory testing: samples are exposed to pure cultures of fungi under optimised conditions, for example, BS EN 113 (BSI, 1997), DD ENV 12038 (BSI, 2002), or to laboratory-based soil burial, for example, DD ENV 807 (BSI, 2001).

Each approach has its benefits and drawbacks: outdoor exposure may be more representative of operating conditions but takes considerably longer to obtain results, whereas laboratory testing relies on optimized and monoculture conditions, but will give results in a much shorter time frame.

The basis of current durability testing is therefore based around whether and when a certain timber species will require preservative treatments in order to be used in certain conditions. Other very similar tests (BS EN 113 (BSI, 1997)) are used to test the efficacy of traditional or novel preservative systems.

How does modified wood fit into this testing regime? Generally current practice is to use the existing testing standards; for example, considering the modified wood to be a novel species of timber and testing its natural durability according to BS EN 350 (BSI, 1994a). In research testing, however, different levels of the same modification may need to be compared, meaning an BS EN 113 (BSI, 1997) style test would be appropriate, but with an adjusted set of calculations for the weight change due to treatment, and the level of protection afforded. This is just one example where the scientist must make an informed decision to alter the standard method appropriately for the task in hand.

Further aspects require consideration for accelerated laboratory testing. Laboratory testing uses optimised conditions and pure cultures of fungi. The malt agar growth medium in the test jar has been selected not only to support the fungus throughout the test, but also to help maintain the appropriate relative humidity to ensure that the wood is at a high enough moisture content for fungal activity. Indeed if the wood does not reach the required moisture content then the test may be invalid according to the strict interpretation of the standard. However, one of the main reasons that acetylated and thermally modified wood have improved in-service durability is that the wood–water interactions are affected in such a way that the EMC of modified woods is lower than the equivalent non-modified wood (Peterson and Thomas, 1978; Suttie *et al.*, 1997). A value judgement is therefore required as to whether the standard seeks to simulate what would occur in a given relative humidity environment, or whether the environment should be modified to increase the moisture content of the test samples so that fungi can begin to act. In a system which seeks to perform as a biocide-free alternative to traditional products, the former solution may be appropriate, but can this be transferred to on-site performance?

In the commonly used accelerated tests where there is an ample supply of moisture, there is a risk that the main durability enhancement mechanism will be nullified by the testing conditions, leading to incongruous results. An above ground outdoor exposure test should provide more realistic results, but the time required for such tests can be too long-term to usefully assist with decisions during product development. Therefore when utilizing accelerated tests, or indeed outdoor exposure tests, an understanding of the test methodology is important in understanding the data derived from the test. The limitations of each test also need to be understood to accurately assess experimental data.

3.2 Mechanical properties

The mechanical properties of acetylated, thermally treated or furfurylated wood can be altered compared to the equivalent timber prior to modification, as has been mentioned in the review above, which focused on work at the laboratory scale. In the case of construction with modified timber the correct bending, compressive and tensile strength values are required for calculations within Eurocode 5 (BSI, 2004b), some of the predictions and assumptions made in deriving these values have been shown to be very case-specific, and previously derived correlations, for example between bending modulus and other strength properties, cannot be assumed to be linear or to align with the calibration data based on untreated wood.

In practice, this may be of limited immediate concern as thermally treated wood is predominantly used in cladding and decking applications or interior joinery, while acetylated timber, although demonstrated in large structures such as the Sneek road bridges (Figure 4, Accsys Technologies, 2014b), is finding a significant market in window joinery due to its 50-year service life and high dimensional stability.

In future, a greater number of structural projects may embrace the modified timbers, and derivation of Eurocode 5 strength values is essential to facilitate this process. A good data set for Accoya has been produced (Accsys Technologies, 2014c), while the development of Eurocode values for thermally modified timber was the focus of a European collaborative research project, and reveals some interesting considerations, as discussed below.

There has been some interest in assigning a strength class to thermally modified wood, and a European-funded project looked in detail at potential grading systems for thermally

Figure 4. Glued laminated timber bridge, formed using acetylated radiata pine to carry traffic up to 65 t, built in 2008 at Sneek, the Netherlands (courtesy of Accsys Technologies plc)

treated beech (Widmann and Beikircher, 2010). The beech was from a commercial treatment by Mitteramskogler, Austria, at the 'Forte' level of treatment. The density of this timber had been reduced from 670–820 kg/m^3 to the range 500–800 kg/m^3 by the treatment.

Mechanical stress grading systems for timber rely on the relationship between density, MOE and the MOR (or breaking load). As thermally modified timber tends to fail at a lower load than unmodified timber, but has a similar or sometimes increased MOE, it is therefore not possible to use standard machine grading settings to assign strength classes to thermally treated wood for use in construction.

The failure mode seen in the Widmann and Beikircher study, for bending tests on thermally treated beech, was the brittle mode, and failure was frequently almost explosive – generating dust and small particles. In general, the thermally treated timber mean bending strength reached only 65% of the mean bending strength of the untreated timber. The fifth percentile of the two sample populations is generally used in structural properties determination, and this value for thermally treated beech was 50% of the value for untreated beech. A characteristic bending strength for thermally treated beech was calculated as 30·9 MPa, indicating strength class D30, but within the sample population one sample failed at 16·2 MPa, so the standard calculation under BS EN 384 (BSI, 2004a) has not fully prevented catastrophic failure in service (Widmann and Beikircher, 2010).

When the MOE in bending was calculated on the basis of global mean, the $E_{\mathrm{o,mean}}$, the value for thermally treated beech was 16·0 GPa. This MOE is classified as strength class D50 under the BS EN 338 standard (BSI, 2003). This class would considerably over-estimate the performance of the material, compared to the failure loads seen in MOR data. The discrepancy in estimation of strength class for thermally treated timber clearly indicates a need for caution in using structural data derived from MOE test values.

Similarly, when looking at compressive strength, the thermally treated beech did not fit the established models for untreated timber. By standard calculation based on characteristic bending strength, the predicted value for compressive strength parallel to the grain would be 23·4 MPa. However, in the study the compressive strength of thermally treated beech exceeded that of the untreated beech, and the observed mean of 44·3 MPa would assign thermally modified beech to class D70 according to BS EN 338 (BSI, 2003). In compression perpendicular to the grain the reverse is true, as values for thermally treated beech were lower than for untreated beech. The calculated compression perpendicular to the grain of 6·03 MPa was so low that the thermally treated beech could not be allocated to a hardwood strength class, but would meet (and exceed) the level for a softwood strength class of C50 instead.

Tensile strength data were also examined. More than 60% of the failures observed occurred within the clamping jaws of the test machine, indicating a sensitivity to multi-axial stresses for thermally treated timber. Clamping also led to longitudinal cracks developing during loading of the samples to the machine, and had an effect on the total active cross-sectional area of the samples. This contributed to failure at lower loads than were seen in the untreated beech. The characteristic tensile strength for thermally treated beech was 10·4 N/mm^2 after consideration of the appropriate factors under BS EN 384 (BSI, 2004a). This is very low, and a value of approximately 20 MPa had been expected based on the assumed relationship between bending and tensile properties in unmodified timber ($f_{\mathrm{t,0,k}} = 0{\cdot}6\, f_{\mathrm{m,k}}$ in BS EN 338 (BSI, 2003) and BS EN 384 (BSI, 2004a)).

It is clear from these various results that for thermally treated wood it is not possible to use the established relationships between bending strength and modulus, or between bending strength and tensile strength, or those between compressive strength in the parallel or perpendicular direction. The standards currently prescribe bending tests to determine bending modulus and bending strength (BS EN 384 (BSI, 2004a)). The values for other properties for hardwoods are then determined by relationships set out in BS EN 384 (BSI, 2004a) to assign strength classes (BS EN 338 (BSI, 2003)) in other testing modes. New correlations to specifically accommodate the properties of thermally treated wood would be necessary.

In terms of grading, the use of a handheld ultrasonic meter to measure dynamic modulus gave reasonable correlation with

MOE in bending (Widmann and Beikircher, 2010). This means that a performance prediction for thermally treated planks could be made using this technology; however, the correlation with bending strength was poor. Density also gave a reasonable (but not high) correlation, meaning that this could be used with the ultrasonic data to predict MOE in bending.

3.3 Specifications

Within the EuroNorm framework, certain product categories have specifications for different types of categories. Types of particleboard, for example, have been split into categories ranging from P1 to P7 (BS EN 312:2010 (BSI, 2010)). These categories relate to the intended use, and the typical environmental or loading factors which are encountered, therefore they allow particleboard to be specified without the need to refer to product data from a range of suppliers. Within the specification, minimum values for the required attribute of the boards are stated (and in some cases maximum values) so that the panels will perform as required. The specification also allows panels and panel production to be easily benchmarked to ensure a consistency of quality and of performance across manufacturers. Other standards agencies (ASTM, ISO for example) also write specifications applying the same broad principles in selecting the performance criteria but tailored to their specific regions. Therefore, the minimum specification for a panel as defined by ASTM may be different to the one defined by BS EN.

Several regions have shown interest in developing a method to categorise thermally modified wood by performance classes, or by applications, or simply label products which conform to a set of standards. For example, in Scandinavia, the Nordic Timber Council (NTR) has developed a stamp similar to their system for preservative-treated wood, which can be applied to various kinds of thermally modified wood. This considers the performance method for the wood modification – bulking, cross-linking or thermal, as well as the level of performance achieved in three areas: anti-swelling efficiency, moisture exclusion efficiency and durability in laboratory and field tests. As a result, four classes can be allocated: MOD M; MOD A; MOD B and MOD AB. MOD M is suitable for applications in use class 5, MOD A is for use class 4, and MOD B and MOD AB are in use class 3. MOD B assumes a smaller level of penetration of the modifying chemical into the timber (6 mm into sapwood), compared to the other classes, which should be treated throughout.

In Germany there has been an initiative to develop certification mark TMT for thermally modified timber. This initiative is coordinated by the Entwicklungs- und Prüflabor Holztechnologie GmbH (EPH), who are an EU notified body for certification and testing. The TMT mark can be tested at three levels – interior, exterior and exterior plus. Further details are available from the Institut für Holztechnologie Dresden website (IHD, 2013).

There was some activity in North America to discuss and develop a thermally modified wood standard during 2012, including a whole-day forum meeting and a seminar. The intention was to establish a system similar to the TMT mark developed in Germany. In spring 2014, the AWPA/ANSI guidance document N was published in the AWPA book of standards. This specified the data requirements for listing thermally modified woods in the AWPA standards. It provides a platform of testing protocols and a comprehensive set of evaluation requirements. It offers some clarity to the issues such as decay testing in the American context (Winandy and Donahue, 2014).

So, there is industrial interest in establishing a simple harmonised system of product performance for wood modification to assist engineers and designers in using the products. However, to date there is no such specification in place, and specifiers, buyers and consumers must rely on industry-provided data on a company-by-company basis. Although there is no reason to believe that these data are incorrect, the comparison process is time consuming and may be off-putting when selecting the novel products for an upcoming project. In addition, the methods used and the level of reporting vary from company to company, sometimes with the test method being unspecified, or even inappropriate for the matter in hand. This leads to the consumer having less confidence in the product and can act as a barrier to the uptake of a new product.

3.4 Timber service life

Good prediction of the service life of timber and structural components made from timber is becoming more relevant. This is mainly due to two distinct factors: environmental aspects, and the economic factors affecting the use of the timber components. The environmental factors for the whole life cycle of the product will not only include an assessment of its manufacture but also the environmental cost of the upkeep of the products. For example, assumptions about the paint regime used throughout the life span of a wooden window frame will have to be taken into account when comparing it to a PVC window frame. In a similar situation, the total life cost of the built environment and the length of service life of the materials used in that building are of great importance to the economy of a country or maintaining competitiveness within an industry or corporation (Hovde, 2004).

Within Europe, the construction products directive was implemented in 1988 (EC, 1988), and within this directive it is stated that six specific requirements for the construction products are fulfilled during the economically reasonable working life of the product. The term ‘working life’ can be seen as synonymous with ‘service life’.

Brand (1994) suggests the importance of specifying the service life of individual components of a building as well as the

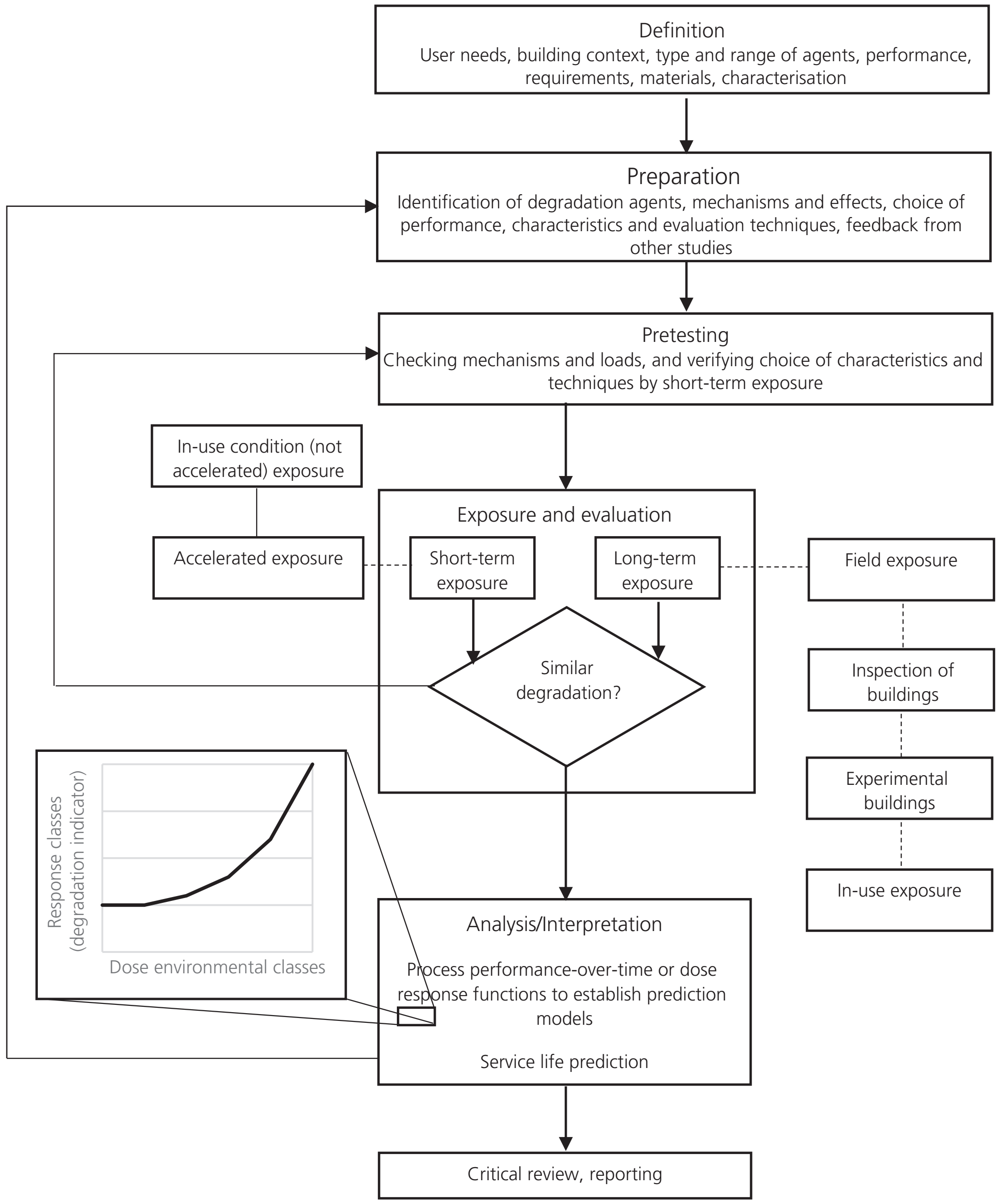

Figure 5. Systematic methodology for service life prediction of building components (from ISO 15686, Part 2 (ISO, 2001))

whole building. He suggests that each part with a service life shorter than that of the whole building should be easily replaced or repaired.

Masters (1987) developed general requirements for the development of service life models and these are listed below.

(*a*) The problem should be defined explicitly before attempting to solve it.
(*b*) Service life should be defined such that (i) it can be measured (quantitatively) and (ii) it can be related to in-service performance.
(*c*) It is necessary to remain open to new approaches and methods rather than blindly accepting those of tradition.
(*d*) Simple and systematic procedures that have a basis in logic, common sense and material science should be used.

(*e*) It is important to be aware that unsystematic, qualitative accelerated ageing test data can be used to make anything look good, bad or indifferent.
(*f*) It is necessary to recognise that (i) it is impossible to simulate all possible weathering stresses in the laboratory, and (ii) it is not necessary to do so anyway.
(*g*) It is essential to ensure that degradation processes induced by accelerated tests are the same as those encountered in service.
(*h*) The degradation factors should be measured.
(*i*) It is important to be wary of the correlation trap.
(*j*) It is necessary to recognise that, by using systematic, quantitative procedure, valid acceleration tests can be developed.

Based on these general requirements, a systematic approach to the methodology for service life prediction was outlined by the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (Rilem) (Masters and Brandt, 1989). The methodology is generic to all building products, and the following principles are applied: the identification of needed information; the selection of tests; the interpretation of the data; and finally reporting. The methodology allows for the growth of the knowledge base and the improvement of the predictions. The Rilem recommendation served as the basis for ISO 15686 (ISO, 2001) and the general principles for service life prediction are outlined in Figure 5.

There are many good reviews and methodology papers of service life prediction models for specific products; for example, Martin *et al.* (1994) for coating systems; Brischke *et al.* (2007) for wood and wood products; Bornemann *et al.* (2014) for wooden commodities; Suttie and Englund (2010) for cladding; and Thaler *et al.* (2012) for treated timber. It is very apparent that the model is only as good as the data that are entered into it. As mentioned earlier, the appropriate standards for the testing of modified timber, the large data sets that are available for traditional timber products, and the understanding of the mechanisms associated with the loss of service life, are not yet fully developed; therefore, any service life prediction for modified timber will have to be treated as conservative in terms of estimations of life span.

The lack of good service life models for modified timber has been a barrier to the implementation of the new commodity products into the market place. This will continue until sound service life predictions for each of the modified timbers are available. In the meantime, traditional materials will continue to be specified in their place.

4. Summary and conclusions

Timber can be modified in a variety of ways and the commercially available modified woods have a variety of improved properties, ranging from colour change to increased durability and dimensional stability. Often, with modified timber, the improvements in properties are coupled with a decrease in other properties; for example, decay resistance may be improved with a thermally modified wood product, but the impact toughness reduced.

It is the understanding of these properties and the relationships between the properties that will lead to an increased market for the products, and an increase in their use in civil engineering and architecture. Good communication of the different attributes of modified wood products and the differences between grades available from the same manufacturer, are required, and must be recognised by the designer or engineer, to ensure the appropriate product is chosen for the situation.

The current standards do not, in general, take into account the balance between simultaneously altered properties of modified timber, such as conflict between improved MOE and reduced MOR. Use of the results without understanding the material or the test conditions can be misleading. This in turn could lead to, at best, dissatisfied customers and, at worst, disastrous consequences. Continued harmonisation of the timber standards and Eurocode 5 to include modified wood is required for the full potential of these materials to be harnessed. It is also imperative that data about the modified timbers are communicated in an easily comparable manner that is compatible with these standards. This will involve continued discussion of the most appropriate way to update standard test methods to provide comparable, reliable and realistic data. Confidence in the products as structural elements will then be able to grow.

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