Original article

Consolidating preservative-treated wood: Combined mechanical performance of boron and polymeric products in wood degraded by Coniophora puteana

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\begin{abstract}
When timber elements in heritage buildings are moderately degraded by fungi and assuming underlying moisture problems have been solved, two actions can be taken: i) use a biocide to stop fungal activity; ii) consolidate the degraded elements so that the timber keeps on fulfilling its structural and decorative functions. The aim of this work is to investigate the mechanical performance of maritime pine wood degraded by fungi after being treated with a biocide followed by impregnation with a polymer product. Three commercially available products were used: a boron water-based biocide, an acrylic consolidant and an epoxy-based consolidant. Treated and consolidated specimens were subjected to mechanical tests: axial compression test (NP 618), static surface hardness (ISO 3550) and bending test (NP 619). Sets of replicates were subjected to an evaporation ageing test (EN 73) after application of the products and also tested for mechanical behaviour. An increase in mechanical strength was observed for both consolidants with no significant influence from the previous use of biocide product. The specimens subjected to ageing showed a slightly better general mechanical performance.

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\end{abstract}

1. Research aims

The objective of the study was to investigate the mechanical performance of maritime pine wood degraded by fungi (with mass loss of less than 20\%) when treated with a biocide product followed by consolidation through impregnation with a polymeric product.

2. Experimental

2.1. Introduction

Wood is a natural biodegradable product but humans have always tried to prevent wood decay and destruction by climate, pests and fire [1]. In fact, once wood is in service and protected it can last centuries, as long as the protective conditions remain stable [2–4]. Building quality and durability are a priority and therefore, solutions that increase and preserve the physical and mechanical integrity of constructions are needed, and this is more demanding when the building has historical value [5,6]. Accordingly, the option of keeping the original timber elements (even though deteriorated) in the building has been gaining importance, because removing them detracts from the building's historical identity. Extensive replacement of elements is both expensive and often also unnecessary: it may change the characteristics of the structure, and it disrupts the normal use of the building [7]. Furthermore, the sustainable use of forest resources means that timber must be used more efficiently and its life in service increased, hence, a greater use of protection technologies [8].

When timber elements are moderately degraded by fungi, and assuming that underlying moisture problems have been solved [3], it is essential to recover or try to improve the physico-mechanical characteristics so that the timber continues to fulfill its structural and decorative functions [6]. The process of consolidating degraded timber by impregnation consists of forcing a specific fluid material into it which, when hardened, will restore its integrity and improve the physical and mechanical characteristics [9–12]. In addition to strengthening the wood structure, the materials used may also provide some protection against biological pests [13,14]. However, it was found that synthetic consolidants, including acryloids and epoxies, do not significantly increase the resistance of wood against fungi [13,14], and may even be themselves used as a substrate [15]. Several authors, when analysing the influence of various synthetic consolidants on the degradation process of spruce (\textit{Picea abies} Karst.) and other species, also found that they do not improve...
resistance to brown rot [13,16,17]. In 1986, Nakhla recommended that a fungicide should be applied whenever the use of synthetic resins was required in wooden works of art [13], and application of biocides became a routine practice in the conservation of art works [14], even though studies about compatibility of different products are scarce.

In the last 20 years of the 20th century environmental concerns, disposal issues and the general public’s perception questioned the use of traditional active substances [18–20]. Currently, when the risk of leaching is not a conditioning factor, one possibility is to use boron because of its characteristics: low toxicity to mammals and good fungicide and insecticide properties [21,22]. Laboratory and field tests have demonstrated that timber treated with boron withstands brown and white rot as well as insect attack [23,24]. Boron treatment may also provide fire resistance and it is cheap and easy to handle [25].

In situations where it is as important to apply a wood preserving and a consolidant, it is necessary to know their combined performance. This study set out to ascertain the mechanical performance of maritime pine wood degraded by fungi (with mass loss of less than 20%) after treatment with a biocide product followed by consolidation through impregnation with a polymeric product.

2.2. Materials and methods

Specimen preparation was divided in two phases: cutting, selection, and fungal degradation of wood in laboratory conditions. The biocide treatment (BC) was then applied, as were the two consolidation products (E and PB), and mechanical tests were conducted (Fig. 1).

Table 1 presents a distribution matrix of products versus specimens and mechanical tests, together with the density groups they belong to. Two control series were tested for each density group. The mechanical properties of the specimens treated and/or consolidated are analysed by density group and the results are interpreted through comparison with the respective control series.

2.2.1. Specimens

Maritime pine (Pinus pinaster Ait.) dry wood was cut into two sizes: 15 × 25 × 50 mm (SHORT specimens) and 20 × 20 × 340 mm (LONG specimens). The wood was taken from different trees, and specimens were grouped by similar densities. The selection of SHORT specimens for testing was in accordance with the physical characteristics specified in European Standard EN 113 [26]: exclusively sapwood, free from defects, maximum dimensional deviation of 0.5 mm in any of the dimensions, annual growth rings between 2.5 and 8 per 10 mm, proportion of late wood in the annual rings not exceeding 30% of the whole. SHORT specimens were subjected to axial compression testing, according to the Portuguese Standard NP 618 [27] and static surface hardness test (ISO 3350) [28]. The size of LONG specimens was established according to the Portuguese Standard NP 619 [29], since these specimens were to undergo the static flexural test.

2.2.2. Wood degradation

The SHORT specimens were exposed to brown rot fungi Coniospuras puteana (Schumach.) P. Karst, for periods of 4, 8, and 12 weeks. Different levels of degradation of the specimens were obtained. Mass loss was determined as a percentage of the ratio between the mass loss and the initial mass of the non-degraded specimens. Before and after the degradation process, the specimens were placed in a conditioned room at 20 ± 2 °C temperature and 65 ± 5% relative humidity (RH); weighing was performed after mass stabilisation. Mass loss levels between 3% and 23% were obtained.

Degradation of the LONG specimens was achieved by exposing them to a natural environment (a calibrated vegetable soil mixture) in boxes with ventilated lids. The mixture was prepared according to British Standard BS15083-2 [30] and the degradation process was run for 6 to 9 months in a conditioned room at 25 ± 2 °C temperature and 80 ± 5% RH. The test specimens were placed inside the boxes such that the outer 50 mm of the specimens were never in direct contact with the moistened soil (Fig. 4(a)). The degradation level was assessed by the modulus of elasticity (MOE) loss. The MOE parallel to the fibres was measured at intervals during the degradation process. This method resulted from the adaptation of two standards [29,30].

2.2.3. Treatment product

The treatment products were selected according to the criteria of low toxicity for mammals, easy application, good absorption capacity and permanence in indoors timber, and biocide efficiency. A boron-based aqueous solution was selected [21] that met these criteria. The impregnation depth achieved when this solution was applied to timber from an old building previously treated with an unknown product was studied by the same authors, with satisfactory results [12]. The active biocide substances of the product (BC) were sodium oxide (14.7%) and boric oxide (67.1%), with water as solvent.

2.2.4. Consolidants

Consolidants were selected for the following characteristics: penetration capacity in the wood, mechanical strength, durability, hardening without shrinkage, easy application, low toxicity, good aesthetics, low price, and ease of acquisition [13,31,32]. Two commercial consolidants were used (E and PB), after selection tests performed by the same authors [33].

Consolidant E (EPO 155® + K 156® – C.T.S. Srl.) is a thermahardening epoxy-based product. The resin component is based on diglycidyl ether of bisphenol A (DGEBA) and the hardener is made of dialiphatic and cycloaliphatic amines. A pot life of 40 min at 22 °C was obtained.

Consolidant PB (Paraloid B72® – Rohm and Haas) is a thermoplastic acrylic-related product currently used as an adhesive and
Table 1
Matrix of samples groups.

<table>
<thead>
<tr>
<th>Samples Groups</th>
<th>Consolidation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample (range of densities)</td>
<td>E</td>
</tr>
<tr>
<td>Mechanical tests</td>
<td>SHORT (631.0 ± 5.0 kg/m³) Compression 0–0</td>
</tr>
<tr>
<td>Treatment</td>
<td>BC</td>
</tr>
<tr>
<td></td>
<td>aged</td>
</tr>
</tbody>
</table>

consolidant for works of art with wood components [32]. Since the penetration capacity of the resin strongly depends on the solvent and on its proportion in the composition [9,34], several preliminary selection tests were performed [33]. Acetone was chosen as solvent at a mass ratio of 80/20 (acetone/PB72). A pot life of 50 min at 22 °C was obtained.

2.2.5. Impregnation tests

The specimens were stabilised in a conditioned room at 20 ± 1 °C temperature and 65 ± 5% RH to a moisture of 12.9%, n = 6, at the treatment time.

Four series of nine SHORT specimens were prepared for testing of each type of combination of treatment and/or consolidation, as shown in Table 1. Two of the series were subjected to ageing and the two others were tested without ageing. Treatment and consolidation of SHORT specimens were both performed by immersion of the blocks in the products for 15 and 20 minutes respectively (Fig. 3(a)).

The amount of polymer absorbed was determined as the difference in mass of each specimen stabilised in a conditioned room at 20 ± 2 °C temperature and 65 ± 5% RH before and after consolidation.

For LONG specimens, products were applied with a brush until wood surface saturation was reached [35], in order to simulate the application of the product to wood in service (Fig. 4(b)).

2.2.6. Ageing test

The ageing test was performed on SHORT specimens by evaporation, according to European Standard EN 73 [36] procedures, to simulate service situation inside buildings. This test promotes the volatilisation of the treatment solvent and consolidation products. Extreme temperature (40 °C ± 2 °C) and ventilation conditions (1 m/s ± 0.1 m/s) to which the treated element can be submitted over time when the treatment is applied inside a building were simulated. The ageing test was performed for 8 weeks at BRE Trust – Building Research Consultancy Training, in Watford, United Kingdom. At the end the specimens were stabilised in a conditioned room (20 ± 1 °C temperature and 65 ± 5% RH) for a week [36] before they were subjected to mechanical tests.
2.2.7. Mechanical tests

The axial compression test (parallel to fibres) was performed in accordance with NP 618 [27] until each specimen failed, and the relevant value was presented in N/mm² (Figs. 2(a) and 3(b)).

The static hardness test (perpendicular to fibres) followed ISO 3350 [28] and is based on the Janka hardness test [37]. It consists of indenting with a half sphere of radius 5.64 mm at a constant speed of 3 to 6 mm/min, under a progressively higher load, and registering the force units at which failure occurs or at which the half sphere is fully embedded (Fig. 2(b) and 3(c)). Wood surface resistance to indentation or specific load level is calculated by equation (1)[28]:

\[ H_{c.90} = K.F_{\text{max}}(N) \]  

In which: \( H_{c.90} \) - hardness, in N;  
\( F_{\text{max}} \) - maximum failure strength, in N;  
\( K = 1 \).

The static bending test with three load points was carried out by applying a progressively greater force at a constant rhythm, until specimen failure, after about three minutes [29] (Figs. 2(c) and 4(c)).

Six degraded specimens and three non-degraded specimens were tested for each mechanical test and combination of products. Furthermore, a similar set of non-consolidated and non-treated control specimens were submitted to each of the mechanical tests.

Each specimen provided a pair of values (ml,s) for each type of mechanical test: ml (mass loss or MOE loss) and s (strength). Graphs were prepared for each treatment and consolidation pair and a regression line was calculated (Figs. 5, 6 and 7).

Each of the graphs for SHORT specimens corresponds to a density group, as represented in the specimens’ series matrix (Table 1). For each group there are two control series: one subjected and the other not subjected to the ageing process.

The numerical interpretation of the graphs on Figs. 5, 6 and 7 is presented in Table 2 as the percentiles of strength increment prompted by each consolidant or boron + consolidant \((t+c)\) in relation to the control specimen \((0)\), determined according to [equation (2)], whose ordinate \( s \) (strength) is obtained from the respective exponential regression lines presented in Table 3, as a function of ml (mass loss or MOE loss).

\[ I_{(t+c),ml} = \frac{S_{(t+c),ml} - S_{(0),ml}}{S_{(0),ml}} \times 100(\%) \]  

Where: \( I_{(t+c),ml} \) - percentile increment promoted by products \( t+c \) in relation to the control;  
\( S_{(t+c),ml} \) - ordinate \( r \) of the regression line of products \( t+c \);  
\( S_{(0),ml} \) - ordinate \( r \) of the control regression line.

The percentile increment of the aged specimens is referred to the control aged specimen and represented by the variation in the consolidation capacity over time, due to the consolidant.

The low dispersion of the mechanical results, expressed by \( R^2 \) values very close to one, confirms a high degree of confidence in the results obtained.

2.3. Results and discussion

The control line obtained by correlating compressive strength in the non-treated and non-consolidated degraded SHORT specimens and corresponding mass loss highlights the great loss of strength due to the increase in the timber’s degradation, which is evident in both test series. Some authors have demonstrated that incipient decay of wood by brown-rot fungi causes measurable strength loss in a ratio of approximately 4:1 strength to weight loss [38,39]. Varying values of mechanical strength for the different control groups in the initial no-mass-loss situation were expected as they were a direct consequence of the different densities of the test specimens.

Both consolidants lead to increased mechanical capacity of the wood in all situations analysed. The analysis was centered on the increments of the consolidated timber’s mechanical strength versus the equivalent values of non-consolidated wood (Tables 2, 3 and 4). Both consolidants promoted an increase of mechanical strength of 20% to 60% for 10% mass loss and of 40% to 120% for 20% mass loss, except for BC-PB, for which the figures were lower. There were significant differences between the consolidants in the resistance to indentation test: it was observed that wood consolidated with
Figure 6. Resistance to indentation versus mass loss of SHORT specimens non-aged and aged: (a) control and treatment; (b) control, consolidation with E and pair treatment/consolidation; (c) control, consolidation with PB and pair treatment/consolidation.

Figure 7. Bending strength versus MOE loss in LONG specimens non-aged: (a) control, consolidation with E and pair treatment/consolidation; (b) control, consolidation with PB and pair treatment/consolidation.

E had higher mechanical capacity increments than wood consolidated with PB. This was especially noticeable in the test after ageing, where the indentation resistance increments reached 123% for 20% mass loss and consolidant E, but were only 22% (0-PB) and 3% (BC-PB) for the same mass loss and consolidant PB. Similar results have been found in previous tests performed by the same authors [33]. An explanation due to cracking and migration of the polymer induced by solvent evaporation as observed by Munnikendam [40] may be found. But this issue will need to be developed by further investigation.

The presence of boron in non-consolidated wood does not greatly change the mechanical performance pattern of the specimens. This was demonstrated by regression lines on Figs. 5(a) and 6(a) and by the values of the BC-0 column in Tables 2 and 3, in aged and non-aged specimens alike. The presence of boron seems to decrease the consolidation effect by 5% to
30% in most of the situations under analysis. However, there are exceptions, such as the absence of reduction of the consolidation effect in the indentation resistance test for non-aged E (BC-E versus 0-E) (Fig. 6b and Table 3).

Ageing induces an increase of mechanical strength in practically every situation, which is more pronounced for consolidant E than consolidant PB. The compressive strength test reveals an increase in the consolidation effect by around 50% for aged and non-aged wood compared with the aged control specimens.

The static bending test of LONG specimens showed a marked improvement of the bending strength of the degraded specimens after treatment and consolidation, though this was only applied superficially by brushing.

### 3. Conclusions

The application of the acrylic and epoxy-based consolidants may increase the mechanical resistance of consolidated wood. Although low levels of degradation may be remedied by the use of consolidants, the original mechanical condition of sound wood is never recovered.

The application of boron before consolidation decreases the latter’s effect but not to a great extent for most of the products combinations.

Artificial ageing (wind tunnel) contributed to the improvement of the mechanical properties especially when an epoxy-based product was applied, i.e. the consolidation effect of this product not only does not decrease, but it even increases, even if a boron-based treatment is applied beforehand, leading to the idea that a post-cure process of the consolidant took place during the ageing procedure.

The pair of products (treatment/consolidant) which showed the best results was BC-E, according to the tests performed, increased wood resistance was observed after the application of these products.

The practical application of the described methodology is considered worthy of development namely when some decrease in timber resistance (up to 1/5 of the original values) can be accepted and any substitution may be seem as an historic loss (e.g. religious architecture - altars and choir structures). Another possible application results from sporadic water leaks that are solved and do not lead to major destruction of the wood. Preliminary work is already in progress to test this approach [41].

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