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CHARRING RATES OF TIMBER

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PREFACE

This work was carried out to test the validity of currently accepted charring rates of timber, both solid and glulam. Of particular interest was the charring performance of two New Zealand grown timbers and whether they are affected by the unique climatic conditions under which they are produced.

INTENDED AUDIENCE

This report is intended for code writers, researchers, designers and manufacturers of laminated timber products.

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REFERENCE

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KEYWORDS

From Construction Industry Thesaurus - BRANZ edition: Charring; Density-m; Design; Heat; Heat Radiation; Glue Laminated Timber; Loadbearing; Models; Moisture Content; Radiation; Temperature; Timber.

ABSTRACT

This report describes an investigation into parameters that influence charring rate of timber. Firstly, from an international perspective the investigation sought to determine how internal properties of different timber products (solid and glulam) influenced charring, and also attempted to show how two New Zealand grown timbers differed from overseas grown timber, and why any differences existed. Secondly, the different charring rates produced by exposure to test and real fires are considered.

Two tests were performed: the first to demonstrate a model's ability to predict charring rate of various samples prepared with different physical parameters. The second test attempted to relate comparative results from the first test to a heavy section beam or column.

Results from this study indicate that revision of methods used to design timber structures for fire resistance is warranted. The present practice of assuming the charring rate of Radiata pine is 0.6 mm/min is found to be valid only for higher density timber. Selection of a charring rate based on the timber density is much more reliable, especially for timber of lower densities.

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INTRODUCTION

1.1 Problem Description

To calculate fire resistance ratings of timber members, it is assumed that the charring rate of timber is 0.6 mm per minute. This figure is widely accepted both in New Zealand (SANZ 1989), and overseas. It has been the subject of extensive published research.

Glue-laminated (glulam) timber is being used increasingly in New Zealand. It is assumed that its charring rate is the same as for solid timber and fire engineering calculations are based on this assumption. However, recent experimental work at Building Research Association of New Zealand (BRANZ) has indicated the charring rate may be significantly higher for loaded glulam beams (Lim and King, 1990).

Concern has also been expressed that the vast majority of research into fire performance of timber is based on overseas studies concerning timber species grown mainly in the Northern Hemisphere. Timber grown in New Zealand exhibits some differences because the relatively temperate climate causes more rapid growth rates, wider ring spacings and greater variability of density across the annual rings (NZ TRADA, 1971). This study investigates the extent to which these factors adversely affect the charring rate.

1.2 Objective

The overall objective of this work is to determine the factors which influence the charring rate for both solid and glulam timber, and to determine experimentally whether the established figures are applicable to timber used in New Zealand.

From this work a greater confidence in the use of timber in fire rated constructions can be gained.

1.3 Approach

Several models for char prediction were evaluated from literature searching. One of these models (White, 1988) was selected because it was relatively easy to apply and was able to quantify a range of internal wood properties which influence charring rates. Fire exposure conditions, e.g, radiation levels, fire load, oxygen supply and duration were also considered, and their general trends were recorded.

The charring performance of two New Zealand timber species, Radiata pine (solid and glulam) and Douglas fir (solid only), using various combinations of physical properties, were evaluated experimentally and compared with White's 1988 model.

In a second test, a section of glulam was exposed to fire on three faces in the pilot furnace. This test aimed to determine if the current procedure for calculating fire-resistance in timber structures is still valid.

2. LITERATURE REVIEW ON CHARRING OF TIMBER

2.1 Research in New Zealand

Research conducted in New Zealand concentrates mainly on literature searches of overseas sources, with very little experimental work conducted locally.

Kenna (1973), in a review of "timber structures and fire" noted that no experimental data exist for New Zealand timbers, and recommended tests be made on suitable timbers in combination with suitable glues and fire protective treatments. Using data on Douglas fir reported in Shaffer (1967), 0.6 mm/min is found to be a reasonable average value for charring rate of wood. When the wood is light and dry 0.8 mm/min is a better approximation; when it is moist and dense 0.4 mm/min is better.

The current recommendation for charring rate in New Zealand is 0.6 mm/min (SANZ, 1989).

2.2 Modelling of Charring Rate

In Scandinavia and the United States, where the vast majority of research has been conducted, modelling of charring rate has received considerable attention. Thus, the various parameters that charring rate depends on have been identified and in many instances quantified.

These parameters can be divided into two groups as follows.

1. Internal factors such as physical and chemical properties of the timber, density, moisture content, transport properties, chemical properties, orientation of annual rings and perhaps if the timber is solid or glulam.

2. The fire exposure conditions such as incident radiation, available oxygen, thermal inertia of the furnace walls, or surroundings in a real fire.

This work aimed to determine whether New Zealand timber charred at a different rate to overseas timber, and if so, why. If the accepted char rate of 0.6 mm/min is wrong, a revision may be necessary to validate New Zealand structural design methods for fire resistance based on timber.

To compare New Zealand and overseas timber, a model capable of predicting the charring rate from a selection of input data was required. Input data was based on the physical properties of some timber samples, from which wide property variation could be tested. The model could then be used to explain any deviations of New Zealand timber from the established figures for charring.

Several models were evaluated. Although most of them agree on the effects of various parameters on charring rates, only White (1988) provided a means of readily comparing the results of practical charring tests. This model (Appendix 1) was able to be programmed onto a spreadsheet and used to evaluate what influences charring. This formed the basis of the experimental programme later in the project.

2.3 Factors Which Influence Charring Rate (White, 1988 and Schaffer, 1967)

2.3.1 Physical and Chemical Properties

Density: Wood density has a major influence on charring rate. Higher density wood has a slower charring rate.

Moisture Content: Moisture content has a significant influence on charring rate, and it is accepted widely that there are several mechanisms contributing to this. Some of the effects actually tend to oppose each other but the net effect is that increasing moisture content will reduce charring rate.

Permeability: The influence of permeability is shown (Schaffer, 1967) by comparing published charring rates of Southern pine, White oak and Douglas fir corrected for the effect of density. The less permeable species, Douglas fir and White oak, have slower char rates, particularly at higher moisture contents. Permeability controls the movement of moisture in charring timber by affecting the pressure gradient created by moisture evaporation, particularly at temperatures above the boiling point of water. Thus less permeable timber, by (having a greater) pressure gradient does not allow rapid moisture loss, effectively reducing the charring rate (See Table 1).

Chemical Composition: Interspecies differences in wood charring may also be due to chemical composition, since this influences the kinetics and energetics of pyrolysis.

Anatomical Effects: If the ratio of longitudinal to transverse permeability is large, e.g., 20,000:1, then small changes in grain angles can cause large increases in moisture movement, in what appears to be an across-the-grain direction. Rapid moisture loss can result in increased charring rate. Similarly the orientation of the annual rings has also been found to be a factor. If charring is in the direction towards the inner growth rings, a thick layer of ash builds up and the charring rate is slow. When charring is in the opposite direction, less ash accumulates and the wood chars significantly faster.

Timber Treatment: An additional concern affecting the combustibility of timber, is "after glow". This is when exothermic materials continue burning after the external heat source has been removed. This can occur, in timber which has been treated with Copper Chrome Arsenate (CCA) preservative, after just a few seconds of contact with a grassfire (Institution of Engineers Australia, 1989).

However, the charring rate of such treated timber under fire attack appears no different to that of untreated timber. Provided fires are extinguished and hot spots damped down afterwards the risk of after glow is minimised.

2.3.2 Test Conditions

Variations in test conditions may contribute significantly to the measured char rates of timber specimens at least as much as the timber properties themselves. Some parameters to consider are:

1) level of incident radiation on specimens,

2) thermal inertia of furnace walls and temperature variations within the furnace,

3) greater oxygen content in the furnace atmosphere leading to more rapid combustion of specimens,

4) fuel used in furnace (gas or diesel).

2.3.3 Level of Incident Radiation on Specimens

Butler (1971) considers charring rates to be a function of incident radiative energy. The charring rate is a linear function of irradiance with little dependence on species, thermal source or method of measuring char depth. For radiation levels of 20kW/m^2 to 3.3 MW/m^2 the rate of charring follows the relationship:

$$\text{Char rate} = 21.96 \times \text{irradiance}(\text{MW/m}^2) \quad \text{mm/min}$$

Constant charring rates measured in furnace testing of beams and laminated columns suggests that if the BS 476 (British Standards Institution, 1987) "standard time-temperature curve" produces a char rate of 0.66 mm/min, then the radiation flux is equivalent to 30 kW/m^2.

Mikkola (1990) reports on the relationship between radiation and char rate based on some cone calorimeter tests. For a heat flux range of 20-75 kW/m^2) the charring rate is shown to not be very dependent on the external heat flux. The rate of increase of char rate against heat flux is about 50% of that shown by Butler (1971) et al partly because the test method is different. The main differences are that more oxygen is available in the cone calorimeter tests and it has higher radiative heat losses.

2.3.4 Thermal Inertia of Furnace Walls

The thermal inertia of the insulating fire-brick lining the furnace walls is about double that of timber and four times that of charcoal. Therefore, the temperature of the timber should rise faster than that of the furnace walls.

Experimental work at BRANZ by Lim and King (1990) noted that for three parallel glulam beams tested in a horizontal furnace, the charring rate of the adjacent timber surfaces was about 1.15 mm/min, compared with 0.84 mm/min for the timber facing the furnace walls. T. T. Lie (in correspondence 1989) comments on Lim and King's results, by stating that the heat transfer to the centre beam and to the inner surfaces of the outer beams is higher than to the outer surfaces of the outer beams. This may be because the outer surfaces of the beams receive heat from the furnace gases but lose heat to the relatively cooler walls of the furnace. R. H. White (in correspondence 1989) acknowledges that combustible materials such as timber beams in close proximity will increase the radiation to each other. If the furnace burners are turned down to keep the furnace temperatures within the specified time-temperature curve, the temperature between the beams may still continue to rise. This results in an uneven temperature distribution.

2.3.5 Oxygen Content in Furnace and Combustion of Specimen

Combustion of timber (or rather the products of pyrolysis) is also dependent on the oxygen concentration. Mikola (1990) reports that mass loss rate (a measure of charring) reduces by as much as 21% as the oxygen concentration decreases from 21% to 10.5%. Furnaces operate with 10% or less oxygen content, and this must be considered when relating test data to real situations.

Hadvig (1981a), in a study of charring of wood in building fires, concludes that charring rate increases with an increase in opening factor (supply of oxygen). However, other parameters also affect charring:

1) For a given opening factor the initial charring rate is independent of the fire load. However, the greater the fire load, the longer a fire will burn, resulting in a greater final charring depth.

2) If the opening factor is increased, the initial rate of charring is increased and the maximum depth of charring will be reached sooner. For large fire loads, charring continues at the initial charring rate for a longer time.

3) Charring rate reduces as the fire load is consumed and the fire decays.

4) The charring depth reduces for increasing opening factor, as the fire load is consumed more rapidly and the fire decays sooner.

2.4 Fire Performance Of Glulam

Standards such as MP 9: (SANZ, 1989) Fire properties of building materials and elements of structure and AS 1720 (SA, 1990a) Timber Structures, Part 4: Fire resistance of structural members, recommend that the fire performance of glulam be considered as if it were solid timber, but with a qualification on the type of glue used.

Trada (1971a) reports that performance of glulam is influenced by breakdown of the adhesives used. Casein glues break down faster than phenolic or resorcinal glues, which behave similarly to solid timber.

With casein glues there is a 10% greater loss on the char lines. Because the glue is affected by temperature, delamination is also a factor.

Malhotra (1967) reports that charring rate of glulam is relatively unaffected by loading and is typically 0.59-0.69 mm/min. More significant variations in charring rates depend on shapes, glue types, and variations due to species of wood, and the direction of laminations in relation to fire attack.

Trada (1971b) reports an apparent difference between parallel and perpendicular charring in the laminations in softwood beams, a mean rate of 0.646 mm/min parallel to the laminations and 0.767 mm/min perpendicular to the laminations was found. Delamination in the later stages of the test accounted for these differences and it was concluded that char in the direction parallel to laminations was more similar to that of solid wood.

Trada (1971c) found that wood immediately adjacent to a knot tends to char at a faster rate. However, in glulam knots and other defects are largely eliminated, so this effect can be ignored.

Trada (1971d) concluded that, the overall average charring rate for structural timbers for exposures under standard time-temperature conditions, is usually 0.6 mm/min, ranging between 0.8 mm/min and 0.5 mm/min. Higher rates may be expected for timber species with densities less than 400 kg/m^3. Furthermore, char rates are not affected significantly by temperatures normally occurring in building fires.

Olesen (1980) conducted fire tests on loaded glulam beams exposed on three sides (bending with lower surface in tension) and reported the following results.

1) Finger joints on the tension side introduce a severe weakness which can lead to rapid failure, causing accelerated charring of the laminations above.

2) Charring rates were of about 0.6 mm/min and in themselves are unaffected by the loading. However, where a breakdown of the glulam timber occurs (delamination or separation of finger joints) considerably faster charring can result due to the increased surface area exposed.

3) Elevated temperatures in the uncharred parts of the member, considerably reduce the stiffness and strength properties of the timber.

4) Sides of the beams perpendicular to the laminations showed a slightly faster (about 10%) charring rate than the bottom which was parallel with the laminations.

Futhermore (Trada (1971e) reported an increase in charring rate in loaded glulam columns. This was attributed to the degree of adhesion of the charcoal layer to the uncharred timber. If the timber deflects under load it is possible that the protective charcoal layer may dislodge in places, or at least open up, exposing the underlying timber to the fire.

3. EXPERIMENTAL

The experiment consisted of two tests using the BRANZ Pilot Furnace, during which the temperature and pressure were controlled in accordance with AS 1530.4: (SA 1990b) Methods for fire tests on building materials, and components and structures. Part 4: Fire resistance tests elements of building construction.

3.1 Test 1

A specimen holder containing a nominal 1 hour wall with 28 pigeon holes measuring 200 x 100 mm was used (see Figure 1). A selection of timber samples 90 mm in depth (Figure 2) were exposed to the furnace atmosphere on one surface by insertion into the wall, and then removed as required and extinguished. The non-exposed ends of the samples were sealed with resorcinol glue and covered with aluminium tape. The timber samples were selected to cover a range of physical parameters, these were: density moisture content, preservation treatment, species, solid or glulam, annual ring spacing and orientation, radiation and exposure time.

The moisture contents were determined by measurement of the weight loss of oven dried samples.

Timbers were exposed for either the full test time (60 minutes) or during the first 29 minutes, or during the remaining 31 minutes.

Samples exposed during the second period (29-60 minutes) were subjected initially to a higher temperature (817°C) and this increased according to the time-temperature curve AS 1530.4 (SA, 1990b) as the test progressed. Effects of increased level of irradiance on the charring rate were also observed.

When testing concluded, the charred wood was scraped away from the samples and char depth measured.

Seven samples were instrumented with sheath thermocouples to indicate progression of the char front and to verify the charring temperature, (expected to be 300°C; Hadvig, 1981b).

3.2 Test 2

A section of glulam timber measuring 545 mm x 135 mm x 1985 mm, density 452 kg/m^3 at approximately 12% moisture content (density 400 kg/m^3 oven dry) was mounted vertically in the pilot furnace (see Figure 3) and subjected to fire exposure on three sides. The specimen was sectioned at 90 deg in two places, 300 mm above and 300 mm below mid height, and instrumented internally with thermocouples (Figures 4 and 5) as follows: 4 thermocouples 18 mm from the outside surface; 22 thermocouples 36 mm from the outside surface; and spacing between thermocouples was 100 mm on each side and 31.5 mm across the short face.

In the two tests, samples were subjected to temperature and pressure conditions in accordance with AS 1530:4 (SA, 1990a), for a nominal period of 1 hour.

4. RESULTS AND ANALYSIS

4.1 Test 1

The results of test 1 are illustrated in Tables 2.1 to 2.3, covering the exposure periods 0-29 minutes, 0-60 minutes, and 29-31 minutes respectively. Within tables samples are grouped according to other parameters being examined.

Charring rates were determined by scraping away the charred timber and measuring the average depth remaining, to determine the amount lost through charring measured in mm. This was divided by the exposure time and is expressed as actual charring rate in the tables. For the seven 1-hour samples instrumented internally with thermocouples, the charring rates determined by the time taken to reach 300°C (shown in Table 2.4), agreed to within 1%-15% with those determined by the measured char depths after an exposure of 1 hour.

Use was made of density and moisture content data (considered by many researchers to be the two major influences on char rate) and an assessment of the probable CCA penetration depth for the two species. Predictions (based on White's 1988 model Appendix A) of char depth for the exposure time were calculated, converted into charring rates and entered in the Tables 2.1 to 2.3.

4.2 Effectiveness of White's 1988 Model for Predicting Charring Rate

To illustrate the effectiveness of this model, data from Tables 2.1, 2.2 and 2.3 has been plotted on graphs in Figures 6.1, 6.2 and 6.3, respectively. Superimposed on the graphs is the line upon which the data would fall if correlation between predicted and actual charring rates was 100%, i.e., total agreement between predicted and actual values. For the three exposure periods "Pearson's product moment correlation coefficient" was calculated with the following results.

Figure 6.1 illustrates the 29 minute exposure results. The actual charring rate was in all cases less than the predicted charring rate, with a correspondingly low correlation coefficient (58.2%).

Figure 6.2 illustrates the 60 minute exposure time and shows the highest correlation, characterised by an even distribution about the superimposed line (85.5%).

Figure 6.3 illustrates the results for the exposure for the second part of the test (when the temperature and incident radiation are greater). The correlation coefficient (69.5%) indicates a wide variation of results, evident also, is a trend of the actual charring rate being higher than the predicted charring rate.

4.3 Test 2

Results are shown in Table 3, and represent charring rates based on how long it takes for the temperature to reach 300°C at each thermocouple location (see Figure 5).

The mean figures for charring on the left and right hand sides of the specimen (when viewed from the front of the furnace) are 0.68 and 0.87 mm/min, respectively, with a mean of 0.77 mm/min.

The charring rates at the narrow edge of the specimen, i.e., parallel to the laminations, are also shown in Table 3. If effects of corners are ignored, then the char rate at centre thermocouples indicate a marginally slower char rate than at parallel to laminations, 0.68 mm/min compared with 0.77 mm/min for the perpendicular direction.

Measurement of the charred remains at the test's end resulted in the assessment of a mean char rate on sides perpendicular to laminations of 0.73 mm/min and on the face parallel to laminations of 0.63 mm/min.

The thermocouples situated on the gluelines between laminations tended to char faster. This was reinforced by the cross-sections taken at the conclusion of the test shown in Figure 7, as well as the figures in Table 3. Figure 7 also illustrates the variation in char rate between the various laminations.

5. DISCUSSION

Exposure conditions and incident radiation in particular were shown by the literature search to have some significant effects on charring rates. But in real fires the variation in exposure conditions is less extreme producing much more uniform results in terms of charring rate. The internal properties of the timber however, are of more importance in the resulting charring rate.

5.1 Test 1

5.1.1 Exposure Time

Exposure time affects charring rate: as a char layer building up over time acts as an insulating layer protecting the timber underneath, thereby reducing the charring rate. However, this is somewhat offset by the increasing magnitude of the incident radiation as a fire resistance test progresses, or as a real fire develops.

Samples exposed for the second half of the heating period (29-60 minutes) experienced more intense heating (and radiation) in that period, and as expected, charred at a greater rate (see Figure 6.3).

The 1-hour samples which were instrumented with thermocouples at depths of 18 mm and 36 mm are listed in Table 2.4. This shows the mean charring rate measured at each thermocouple depth, and Figure 8 shows the time-temperature responses for sample 7*, from which the charring rate was calculated (on the basis of having exceeded 300°C, Hadvig 1981b). Two of the thermocouples at 36 mm (samples 2* and 4*) had not reached a temperature of 300 °C within 1 hour.

Figure 9 shows a family of curves based on White's model, each curve showing predicted mean charring rate at particular exposure times. Each curve is for a set density at 12% moisture content. Superimposed are the actual test results shown in Table 2.4 (where times are available for both the 18 and 36 mm depth thermocouples). Disregarding the position (on the graph) of the pairs of thermocouple data, which is a function of the particular densities and moisture contents of the test samples, and comparing the relative gradients, it can be seen that in 3 out of 5 cases the gradients are nearly parallel with the curves. For the remaining 2 samples, one showed a constant charring rate whereas the other increased marginally. However, it is not possible to draw any conclusions regarding the effect of exposure time on charring rates.

5.1.2 Density and Moisture Content Relationship to Charring

The influence of density and moisture content on the charring rate is illustrated in Tables 2.1 to 2.3.

Density is the major determinant of charring rate and this should be considered in fire rated designs. For timber of lower density a higher charring rate is used.

The effect of moisture content, although influencing charring rate, is of little consequence. This is because timber will eventually reach its equilibrium state of approximately 12% anyway. However, care should be exercised in areas of application involving low humidity and high temperatures. The timber may appreciably dry out and this increases the charring rate. A 25% increase in the predicted charring rate is not uncommon for completely dry timber.

A correlation coefficient of 85.5% between the predicted and actual charring rates for a 1-hour exposure indicates that the simplified version of White's model, used in this study, can be used as a basis to predict charring rate. However, the method used in test 1 produced, on average, lower than predicted charring rates. This is because edges of the samples were protected and heat was conducted into the surrounding frame. The test standard used in White's tests (American Society for Testing and Materials, ASTM E119) and the BRANZ tests (AS 1530.4), although driven to very similar time-temperature curves, have quite different control thermocouples. This may have contributed to some variation. AS 1530.4 uses bare control thermocouples, whereas ASTM E 119 uses thermocouples in capped pipes. With the capped thermocouples there is a time delay in recording the furnace temperature. Depending on how the furnace is operated, the timber specimens may have been subjected to higher furnace temperatures, especially in the earlier part of a test when the slope of the time-temperature curve is steepest. This may have been reflected in the higher charring rates predicted by White's model, compared with what was actually recorded in test 1; this is especially so for the 29-minute period when the temperature rate rise was more rapid.

The test method was found to be excellent for comparing the charring performance of samples with different physical parameters.

5.1.3 Glulam or Solid Timber

Measured char rates of glulam and solid timber were very similar. Orientation of the glulam did not appear to make a significant difference to the observed charring rate: rates were similar whether exposure was parallel or perpendicular to the glue lines. The glue used in the samples (resorcinol) is one which performs well under fire conditions (Trada, 1971a). Annual ring orientation did not appear to influence the charring rate either.

This first test enabled a valid comparison between the internal influences on charring. However, as samples were exposed to fire on the one face only, comparisons with the behaviour of structural members exposed on multiple faces in tests and real fires is not valid.

5.2 Test 2

5.2.1 Charring rates

In the second test, charring rate varied between means of 0.68 mm/min and 0.87 mm/min for the two exposed sides, with a mean value of 0.77 mm/min overall. The difference in charring rate between the two sides was because the right hand side of the furnace was 10-100°C higher (average approximately 30°C). This was due to two factors: firstly, because the specimen prevented adequate circulation of the furnace gases; and secondly, because burners on the right hand side of the furnace burned with slightly larger flames than burners on the left.

The charred sections of glulam in Figure 7 show the wide variation in charring rates recorded in individual laminations. These ranged from below 0.6 to above 1 mm/min (see Table 3). This is probably due to density variations, which appear to be related to whether the particular laminate is from heartwood or sapwood. Moisture content is assumed to be the same for all laminates. Other factors that may influence charring performance are presence of knots, ring orientation and presence of glue lines. The trends observed were entirely consistent with trends published in the literature.

Charring rate did not appear to decrease as the test progressed; in fact it remained almost constant, with a mean range of 0.75 mm/min - 0.77 mm/min (see Table 3).

Because the specimen was only exposed on three sides charring reduces slightly closer to the non-exposed surface. This is because heat inside the timber is conducted into the wall on which the specimen is mounted, and radiation is lost from the charring surface to the same wall.

5.3 Effectiveness of Model in Predicting Charring Rate

In Appendix A, a worked example using White's model, for predicting charring rate for the glulam specimen tested, shows the predicted charring rate to be 0.76 mm/min. This is based on the time taken for the char depth to reach 36 mm, the depth of the thermocouples. This figure compares very well to thermocouple measurements. On this basis, higher charring rates can be predicted.

5.4 Charring Rate For Design

The results of this study show that the charring rate of 0.6 mm/min as listed in MP 9 is not suitable for fire design purposes with either solid or glulam timber as available in New Zealand, unless timber density is at least 600 kg/m^3 (12% moisture content). Thus some adjustment for charring rate on the basis of density is practical and desirable. Other parameters which influence charring rate may be ignored. Moisture content can be assumed to be approximately 12%. Species influences charring rate, but as 92% of plantations in NZ are Radiata pine, this is not an important consideration. Any other species that may be used in construction in NZ is not expected to have a higher charring rate. Because Radiata pine is a very treatable timber (a measure of the ease of moisture transport in the radial direction (Forest Research Institute, 1988)) , for equal density and moisture content it would be expected to char slightly more rapidly than other species. Therefore, a test method that derived a charring rate suitable for Radiata pine would automatically include species expected to have a slightly lower charring rate.

Two methods currently used to rate timber used in fire-rated constructions were assessed. Both methods take into account expected density variations.

1) The new Australian Standard, AS 1720.4, (SA, 1990), provides a method to cater for variations in charring rate on the basis of density. An allowance is also made for the heat-affected zone below the char layer. It is assumed that this layer has no mechanical strength to contribute to the residual section.

The notional charring rate (mm/min), C, is calculated as follows:

$$c = 0.4 + (280/d)^2 \text{ (mm/min)}$$

d = density at a moisture content of 12% (kg/m^3).

For the sample of glulam tested in test 2 the notional charring rate c is calculated as 0.78 mm/min (density taken as 452 kg/m^3 at 12% mc). This compares very well with the measured mean charring rate in test 2 (0.77 mm/min).

2) Alternatively, BS 5268 : (BSI 1978) Part 4 : Section 4.1 : 1978 Method of calculating fire resistance of timber members, differentiates between different groups of species of timber and assigns specific notional rates of charring for the calculation of residual sections.

However the timbers listed in BS 5268.4 are not those commonly used in NZ, therefore adopting AS 1720.4 would be more practical.

A comparison between the method in AS 1720.4 and the charring rates measured for the air-dried samples in test 1 and the glulam in test 2 is shown in Figure 10. The curve for AS 1720.4, normally based on densities at 12% moisture content, has been adjusted to oven-dry densities for comparison with the test data. With the exception of the oven-dried samples, the measured charring rates for the 60-minute samples are all less than that predicted by AS 1720.4. Selection of charring rates for design on this basis would be expected to give conservative results. Furthermore, AS 1720.4 includes an additional allowance of 7.5 mm on top of the calculated char depth. This takes into account the heat-affected zone when determining the remaining effective residual section for structural purposes.

AS 1720.4 provides a better method for assigning a charring rate for design.

However, a disadvantage with using AS 1720.4 is that timber density must be known at the design stage; in most cases this is not possible.

In practice, this can be overcome by broadly assigning charring rates, in tabular form on the basis of density. If assumptions are made such as: the predominant species is Radiata pine with 12% moisture content and a one-hour exposure, then the following table for values of charring rate is generated using White's model as in Appendix 1.

Density kg/m^3 (at 12% moisture content)	Charring rate (mm/min)
400	0.75
500	0.70
600	0.65

Figure 11 compares the above table with AS 1720.4. Agreement is very close for the 500-600 kg/m^3 range. For the range 400-500 kg/m^3, where there is some discrepancy, White's model gives better agreement with test results. Therefore, it is recommended that this very much simplified table of data derived from White's model should be adopted for design of fire-resistant timber structures in New Zealand.

5.5 Exposure Conditions

Temperature variations within the furnace were not quantified in this study. However, the findings of the literature search support the anomalies reported by Lim and King (1990).

In test 2, charring rate differences between the two opposite faces of the glulam specimen was accounted for by a difference in the recorded temperatures on each side. This temperature difference was because one side of the specimen was subjected to greater heating, due to differing adjustment of burners on each side (discovered during a maintenance check).

5.6 Future Work

The apparatus used in test 1 is suitable for comparing the charring performance of different timber samples. Questions regarding the fire performance of treated timbers are often directed at BRANZ, as are questions concerning the effectiveness of fire retardants. Now that some experience has been gained in the use of White's model and its value as a comparative tool established, comparisons between treated and untreated timber can be performed using White's model to bring the results back to a base-line level.

6. CONCLUSIONS

1. Density and moisture content are the two main factors influencing the charring rate of both solid and glulam timber; whether the timber was grown in New Zealand is not as important.

2. Fire performance of glulam differs to that of solid timber, in the following ways:

   a) Greater charring on glue lines sometimes occurs, depending on the glue's resistance to fire. Increased charring perpendicular to laminations, as opposed to parallel to laminations, can be attributed to this.

   b) Wood adjacent to knots chars at a faster rate. However, this effect is minimised in glulam by selecting better timber, resulting in relatively defect-free composite timber.

3. Deviations from the currently accepted standard figure for charring rate of (0.6 mm/min) have been shown in this project. Revision of the current methods of designing timber structures for fire resistance, including charring rate, is thus warranted.

4. White's (1988) model predicted charring rates similar to test results.

5. It is recommended that the charring rate figure used in MP9 be revised to take into account the contribution of density according to:

Density kg/m^3 (at 12% moisture content)	Charring rate (mm/min)
400	0.75
500	0.70
600	0.65

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APPENDIX 1

Notes on the application of White's model.

A time location model expressed as:

$$t = m x_c^{1.23}$$

or $$\ln t = 1.23 \ln x_c + \ln m$$

and is based on fire exposure conditions according to ASTM E 119

where: t = time of exposure
x_c = depth of char layer
m = charring rate parameter

$$\ln m = 1.3349\, p - 0.009887\, p\, d + 0.1176\, c - 0.003887\, c\, d$$
$$-0.01717\, u - 1.2521$$

and p = density of timber in gm/cm^3 (oven dried)
u = moisture content (%)
d = depth of CCA penetration in mm (transport property)
c = hardwood or softwood classification (1 for softwood or -1 for hardwood)

Attempts to measure CCA penetration were unsuccessful, and figures of 20 mm and 3 mm were assessed for Radiata pine and Douglas fir, respectively, on the basis of White's report, and CCA treatment information on Radiata pine and other species (FRI, 1988).

By assigning the following values c=1 and d=20 or d=3 expressions for ln m are obtained as follows:

$$\ln m = 1.13716\, p + 0.01717\, u - 1.21224$$
for Radiata pine

and $$\ln m = 1.305239\, p + 0.01717\, u - 1.13567$$
for Douglas fir.

by substituting the value for obtained for m into the expression,

$$t = m x_c^{1.23}$$

The time taken for the char to reach a specified depth, and hence the mean charring rate for that period of exposure can be obtained.

Example:

For the glulam specimen as tested, the physical parameters were; density 0.4 gm/cm^3 (oven-dry) and moisture content 12%, ln m is determined using the expression for Radiata pine above.

$$\ln m = 1.13716 \times 0.4 + 0.01717 \times 12 - 1.21224.$$

$$\ln m = -0.5513$$

$$m = \exp(-0.5513) = 0.576$$

Considering a thermocouple at a depth of 36 mm (1 hour for 0.6 mm/min charring rate) the time for the char depth to reach that depth is given by:

$$t = m x_c^{1.23}$$

$$t = 0.576 \times 36^{1.23}$$

$$t = 47.3 \text{ minutes.}$$

This equates to a charring rate of = 0.76 mm/min, which compares very well with the specimen as tested in test 2.

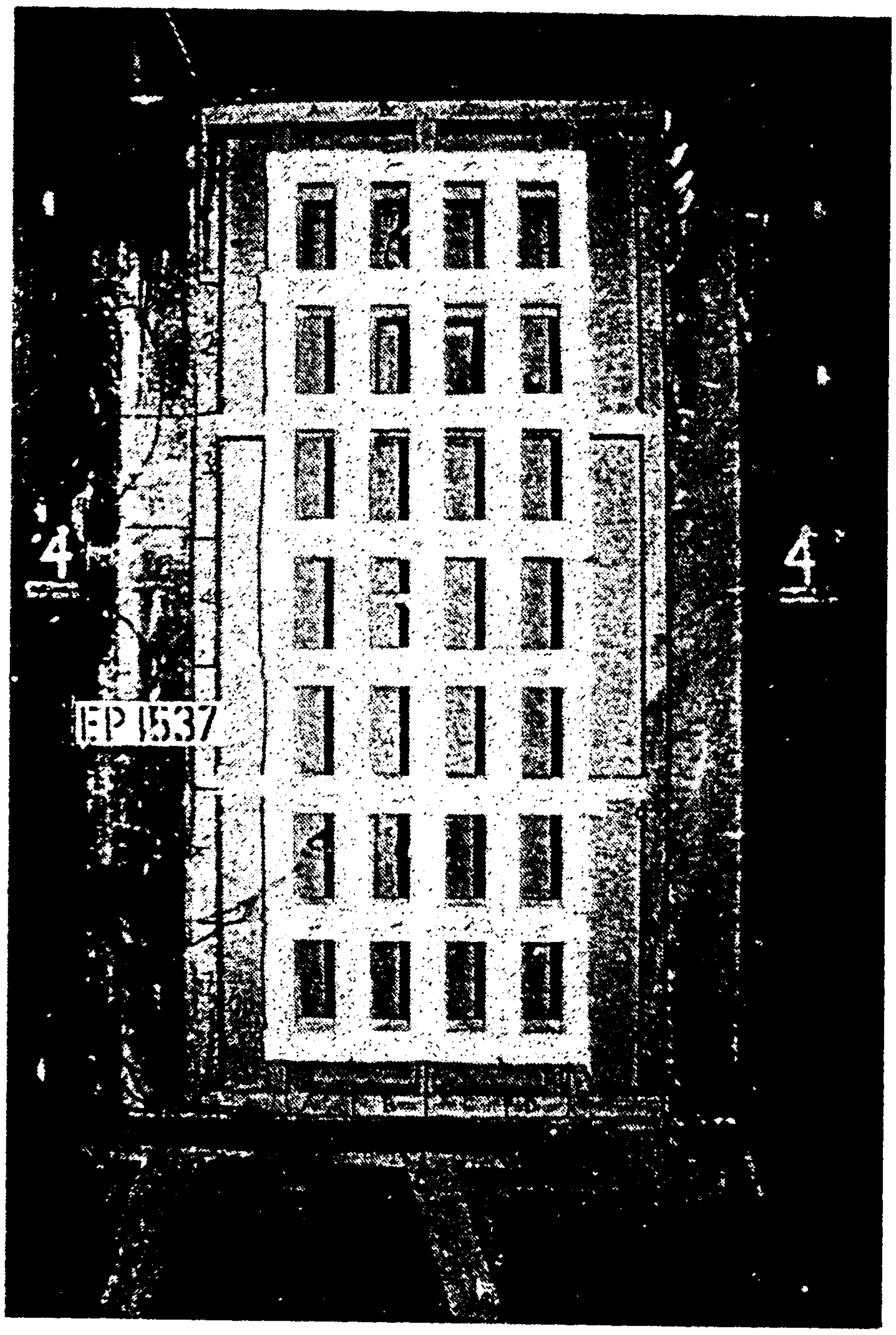
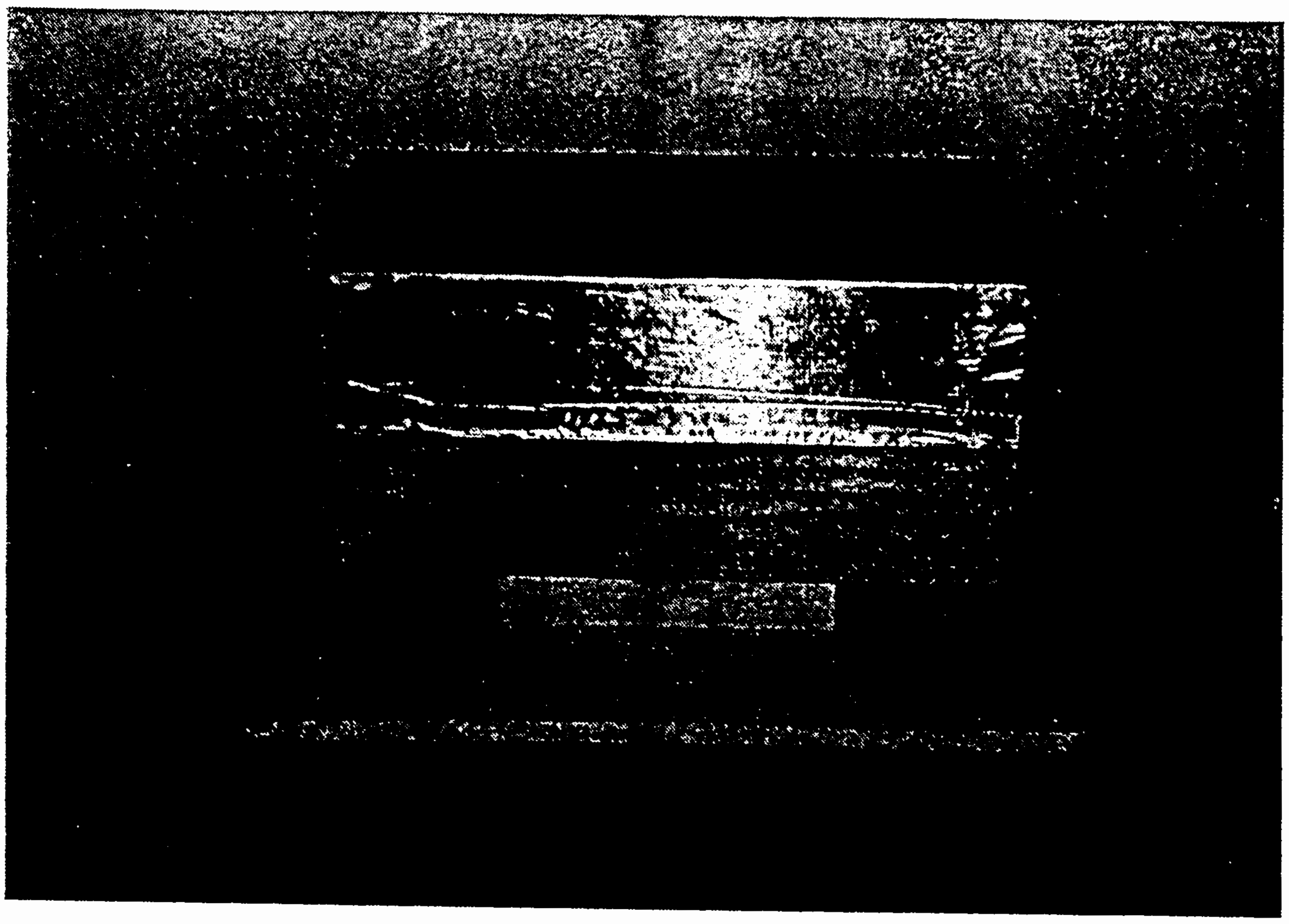


Figure 1 Pilot furnace, with sample holder for test 1.



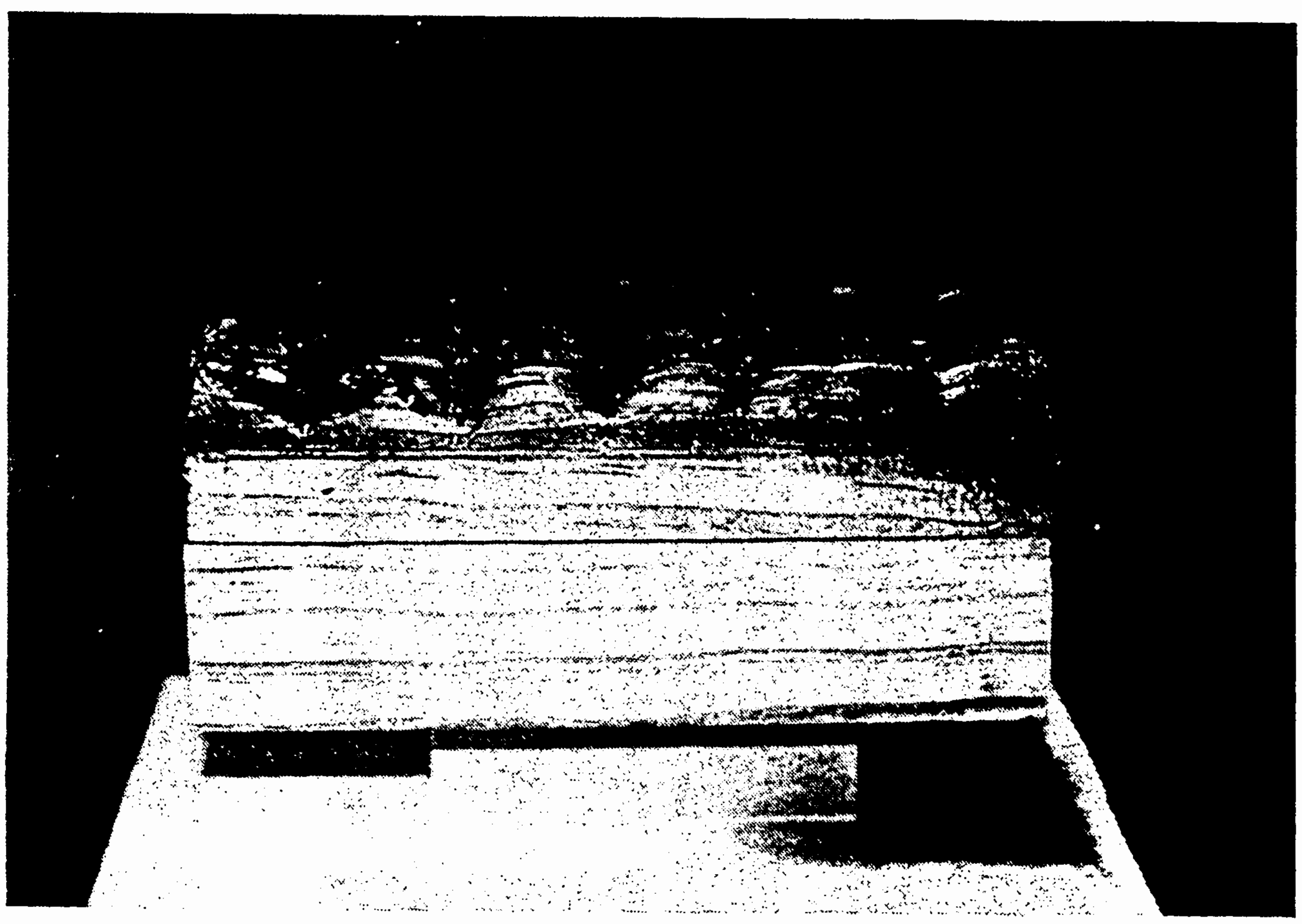


Figure 2 Charring samples.

Figure 3 Glulam in specimen holder for test 2.

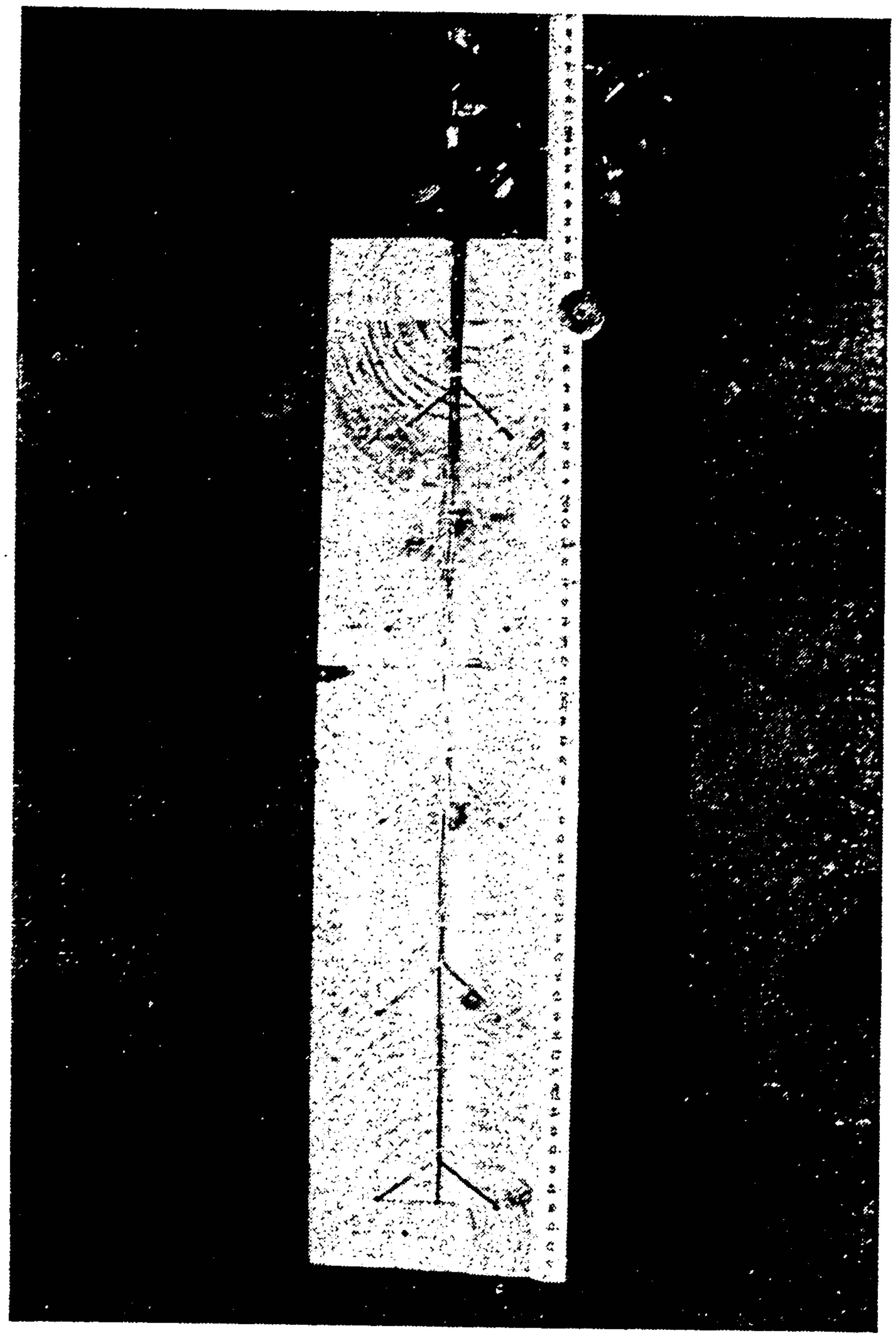


Figure 4 Glulam cross-section showing embedded thermocouples.

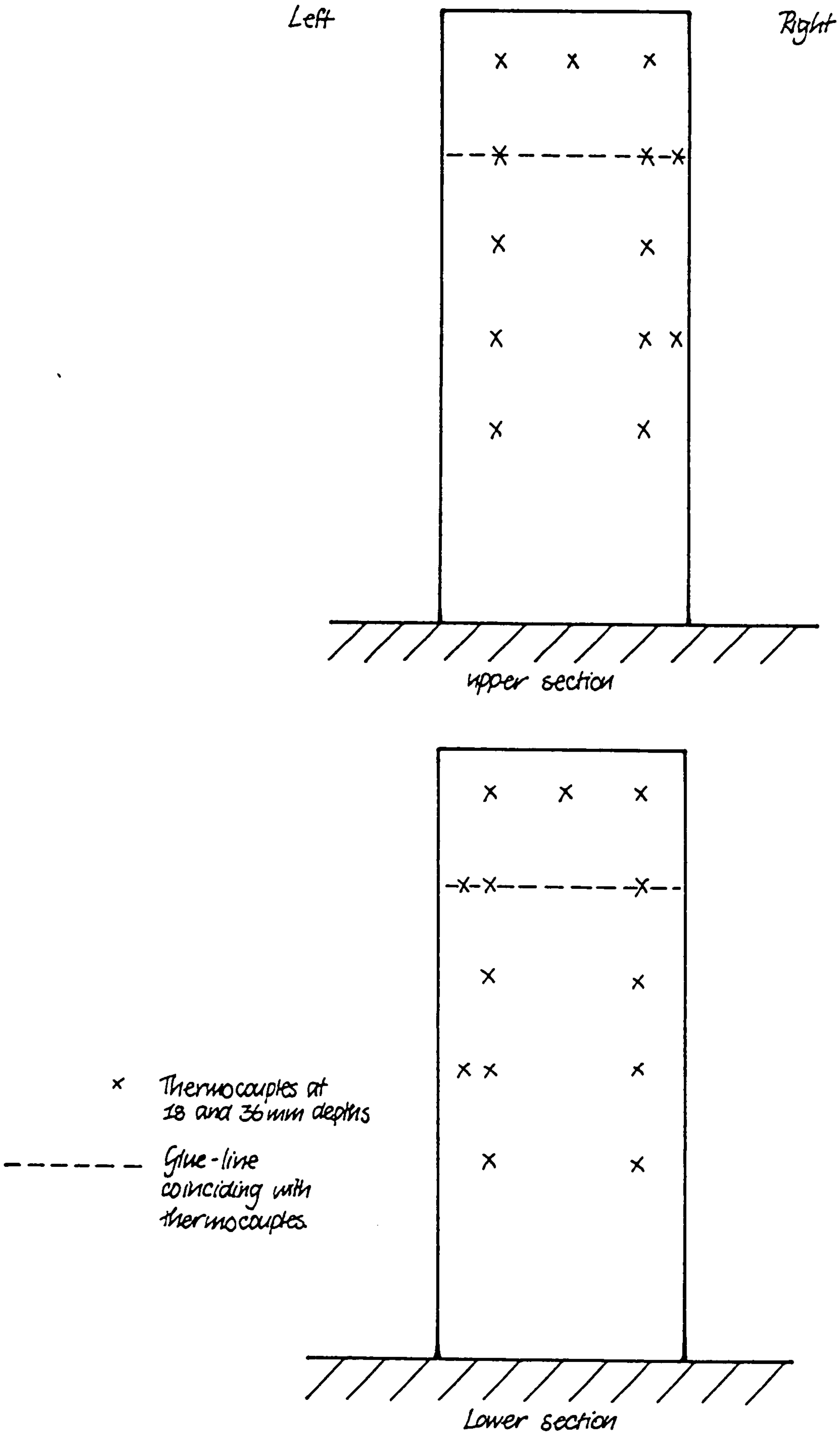


Figure 5 Location of thermocouples in glulam sections.

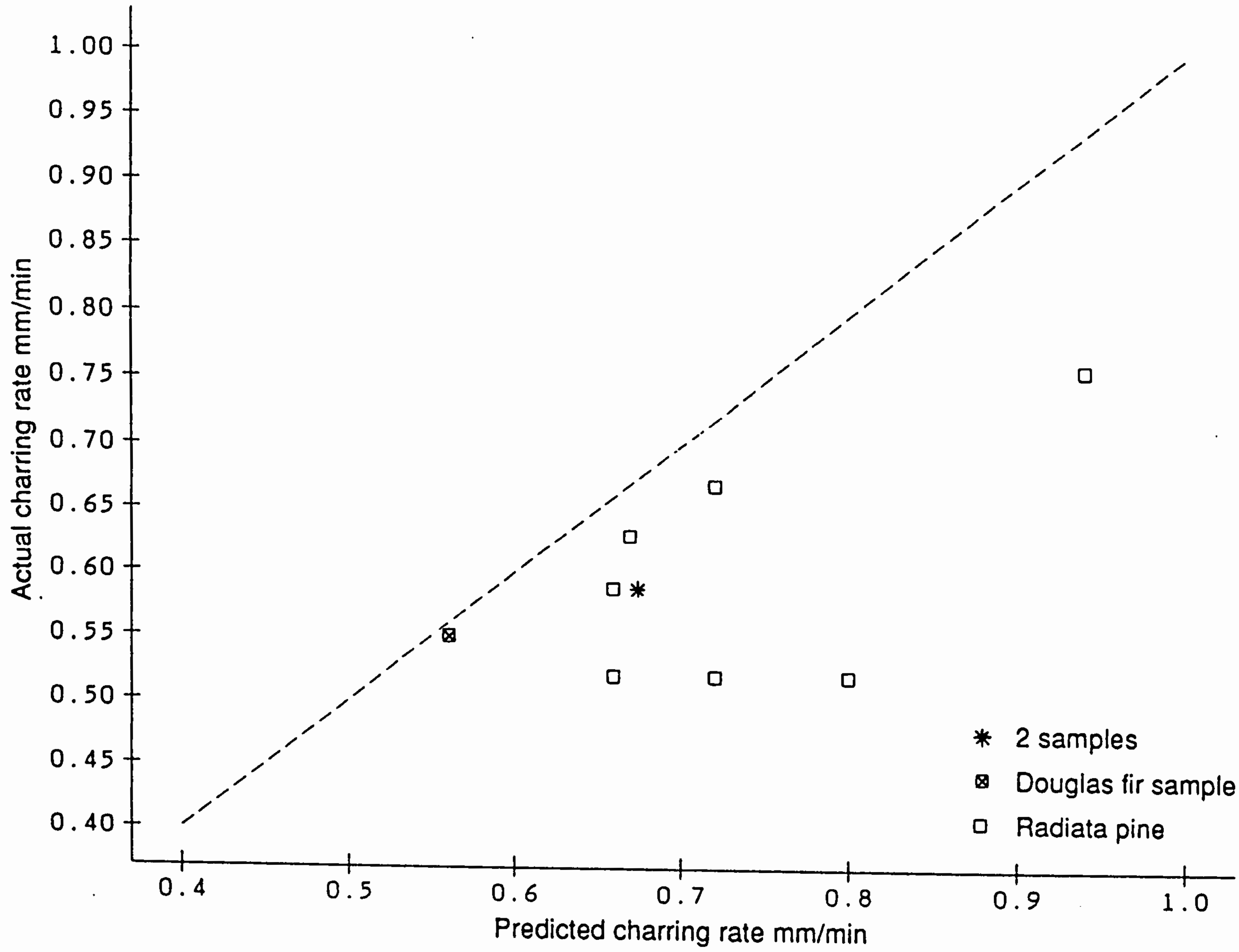


Figure 6.1 Scatter diagram of char rates for 29 minutes exposure

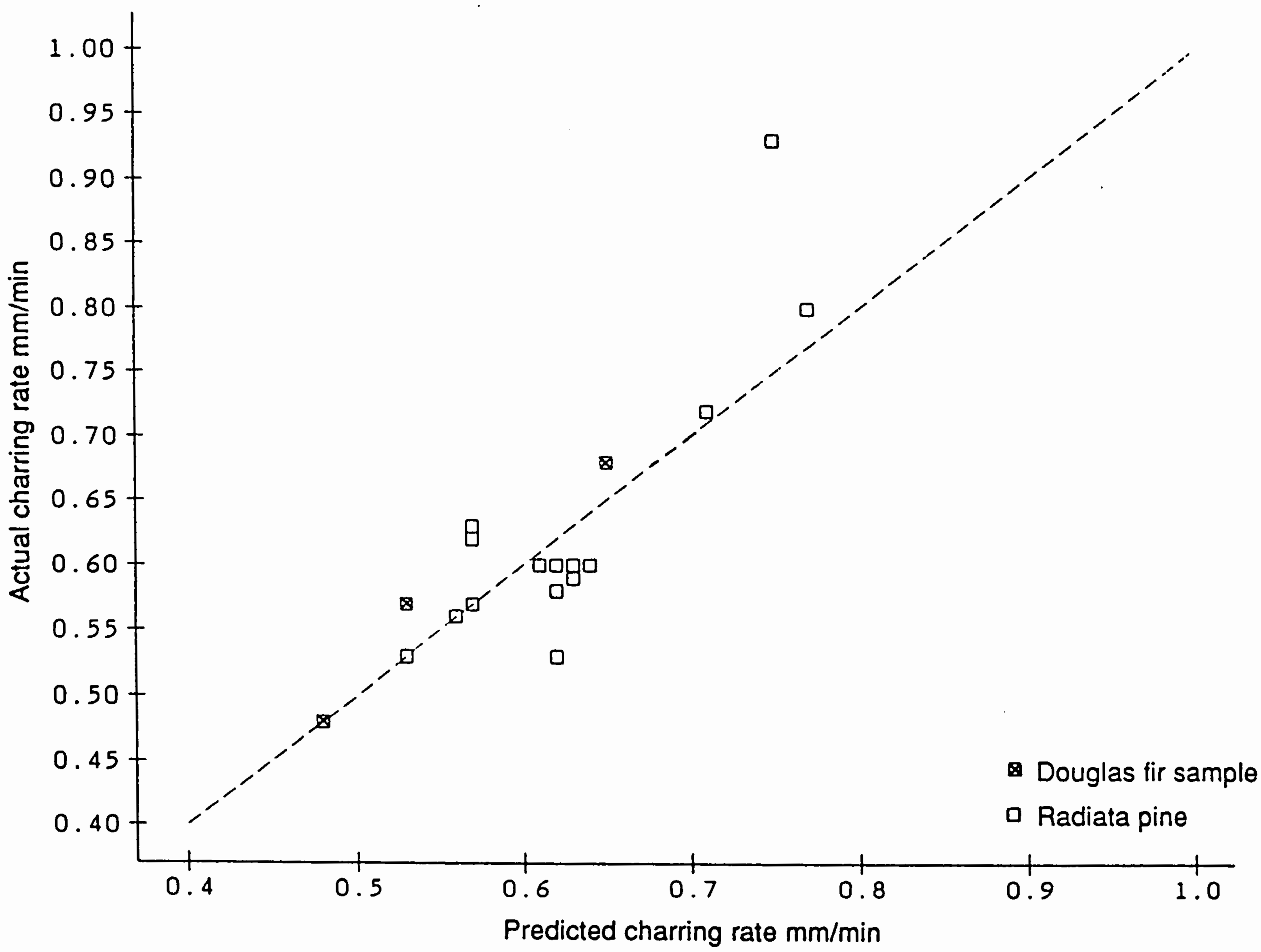


Figure 6.2 Scatter diagram of char rates for 60 minutes exposure

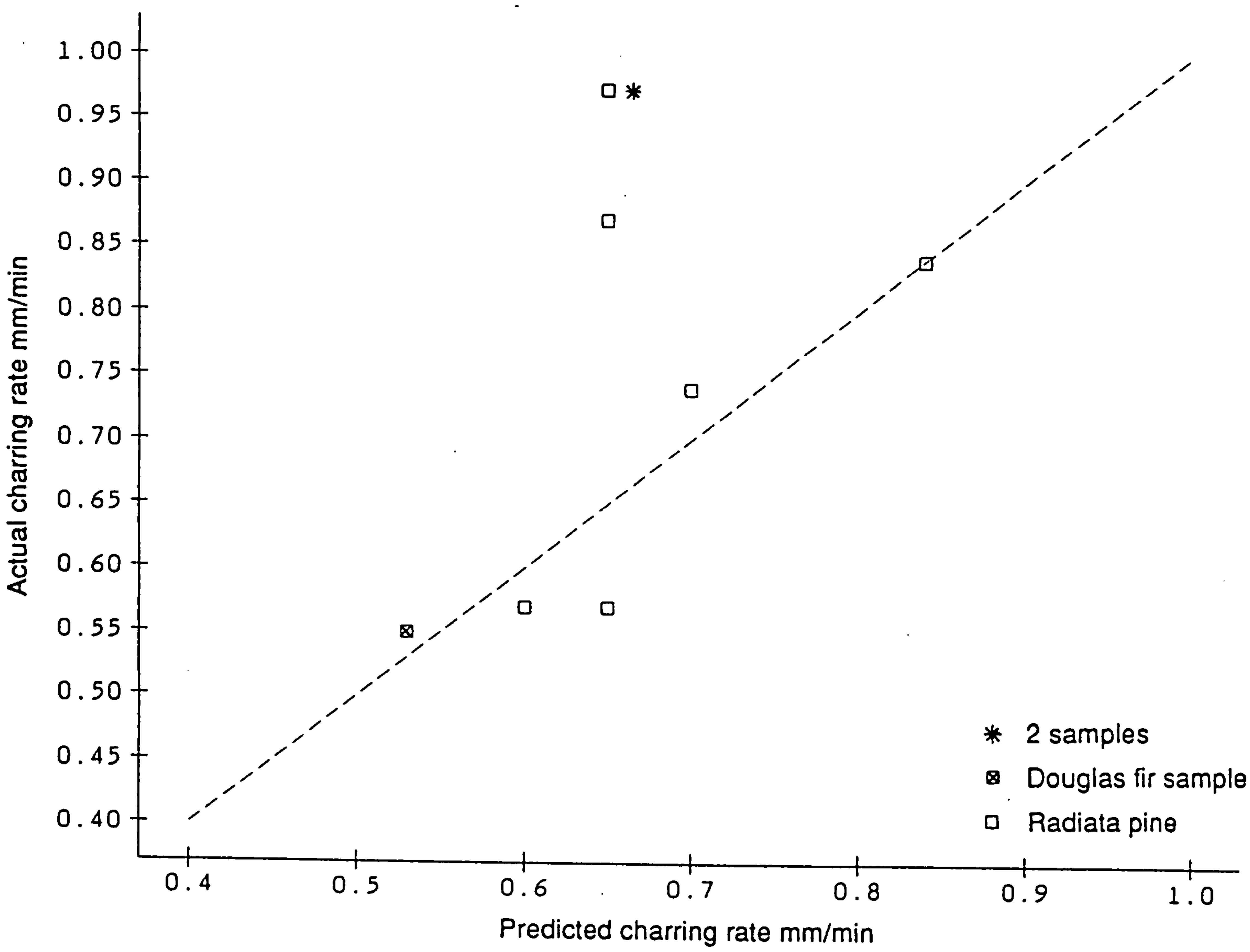


Figure 6.3 Scatter diagram of char rates for 29-60 minutes exposure

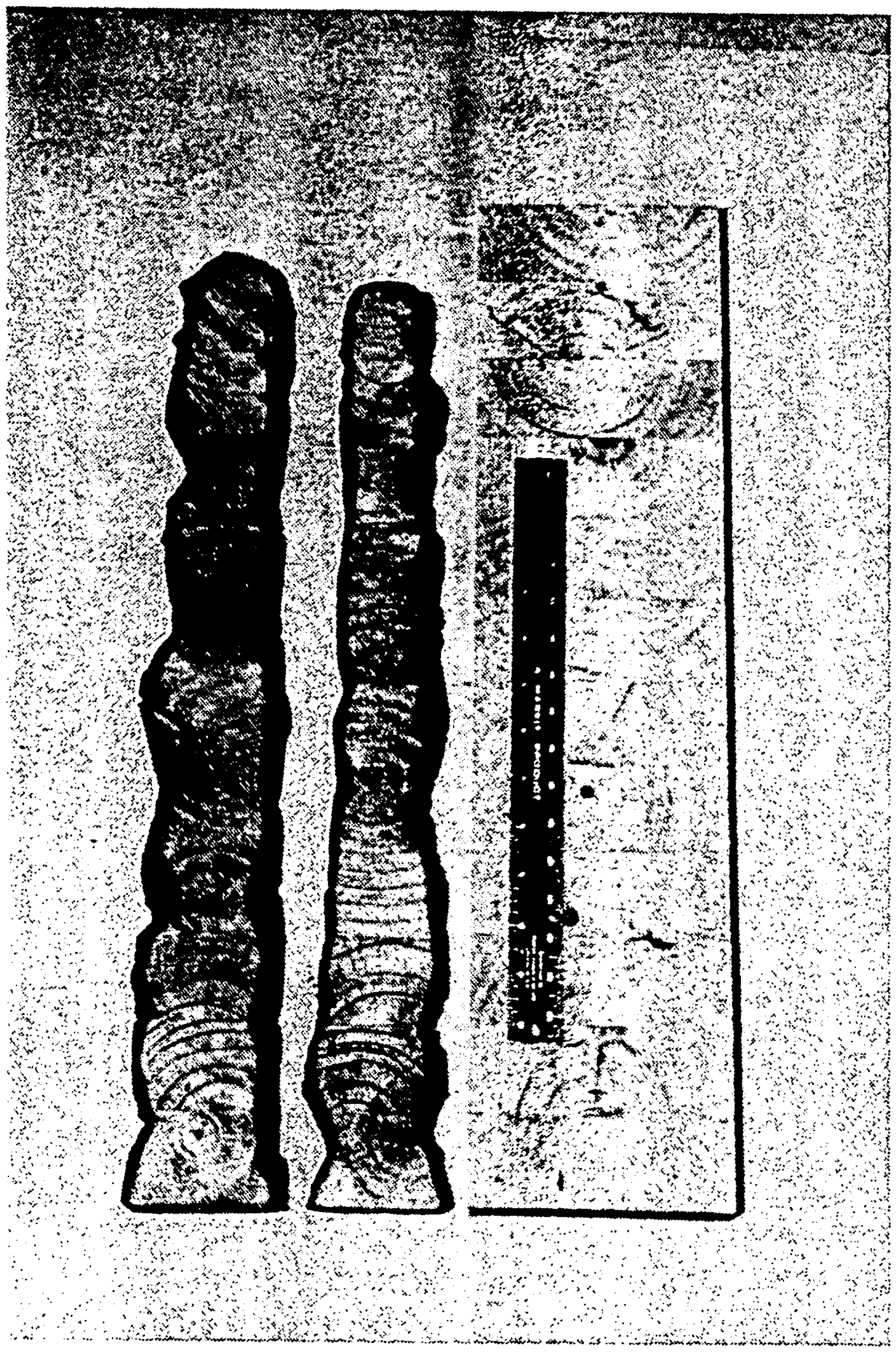


Figure 7 Charred cross-section of glulam after 1 hour exposure.

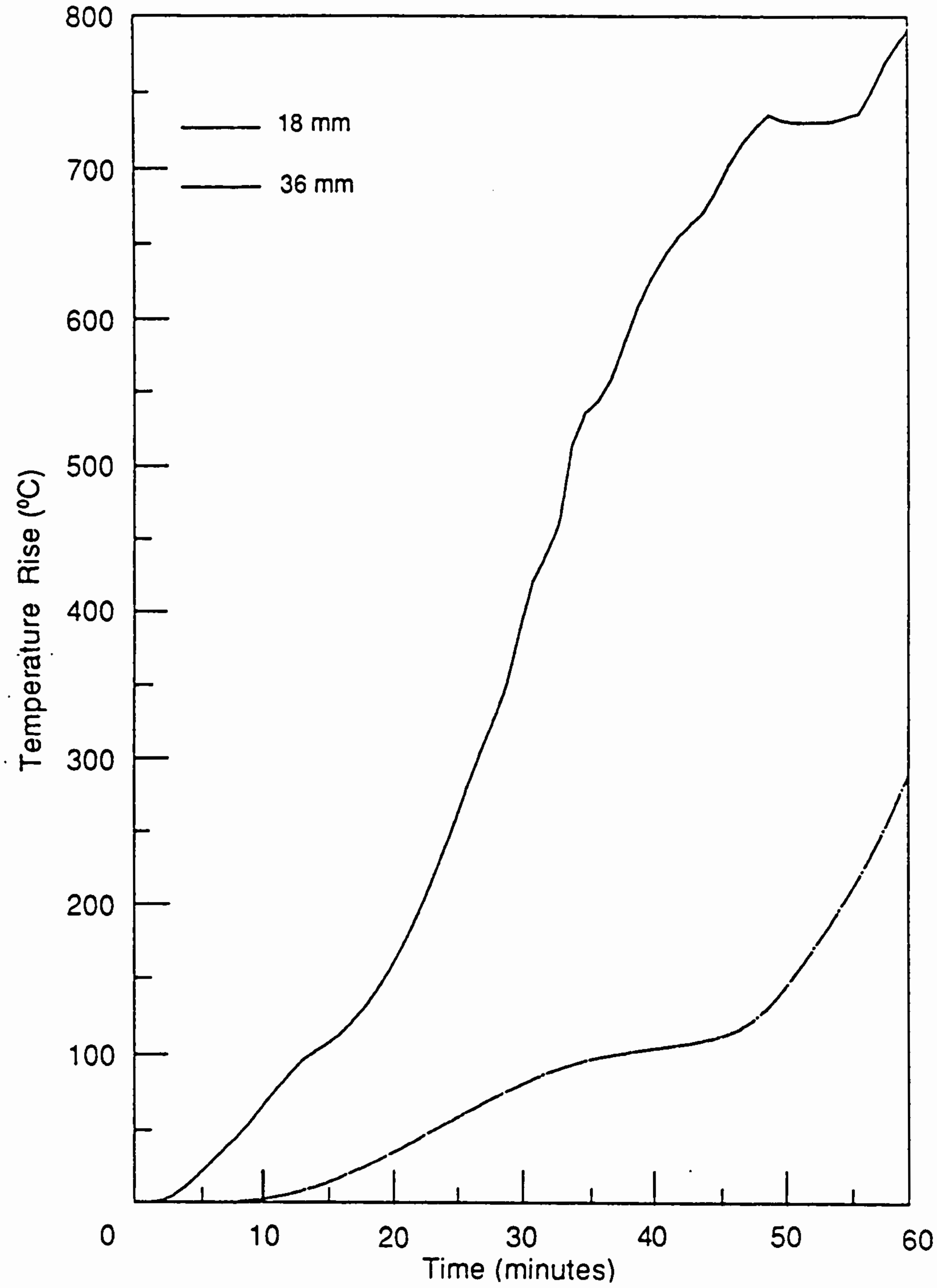


Figure 8 Temperature response of internal thermocouples 18 and 36 mm (ambient temperature 11°C)

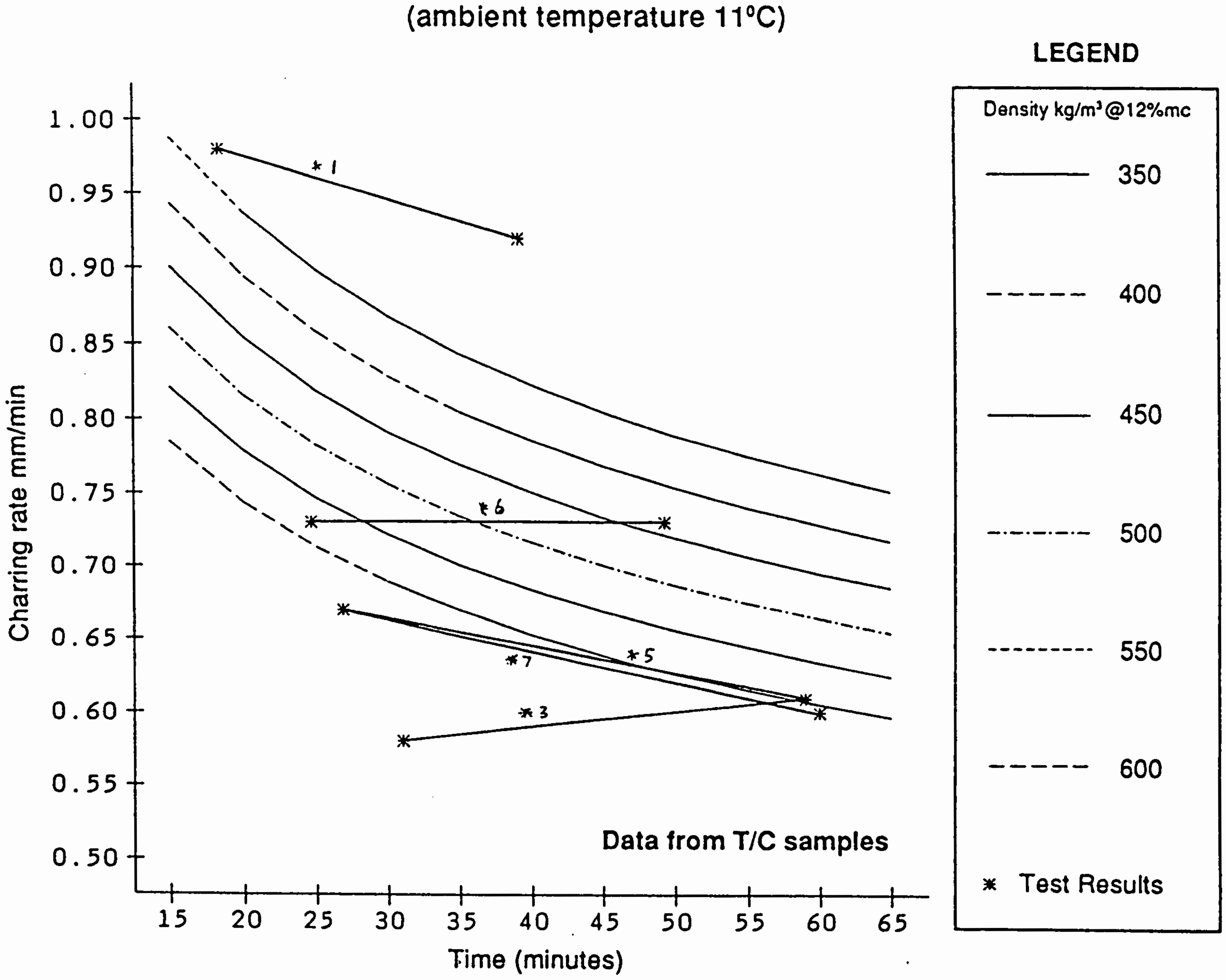


Figure 9 Variation of mean charring rate with exposure time

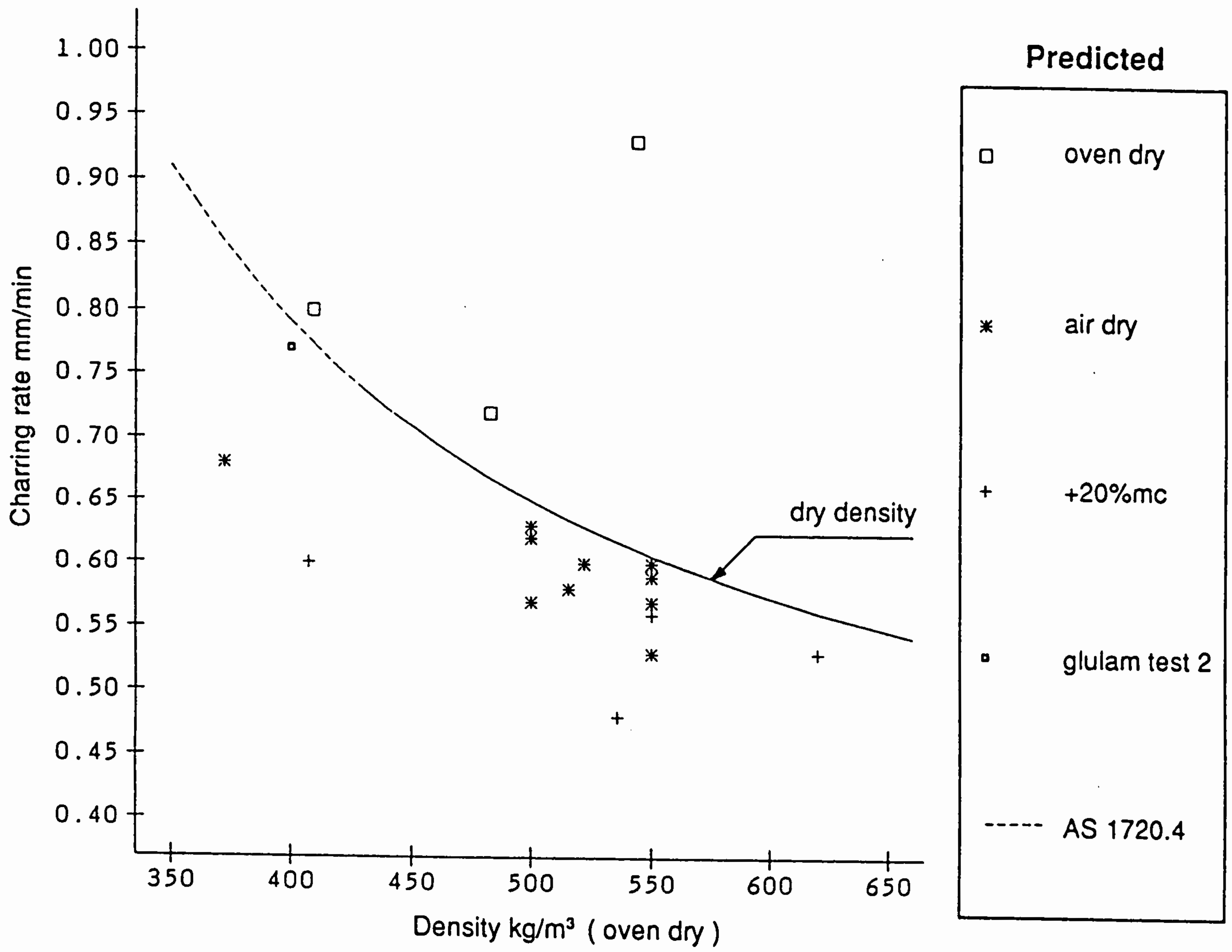


Figure 10 Comparison of test results and AS 1720.4 for 60 minutes

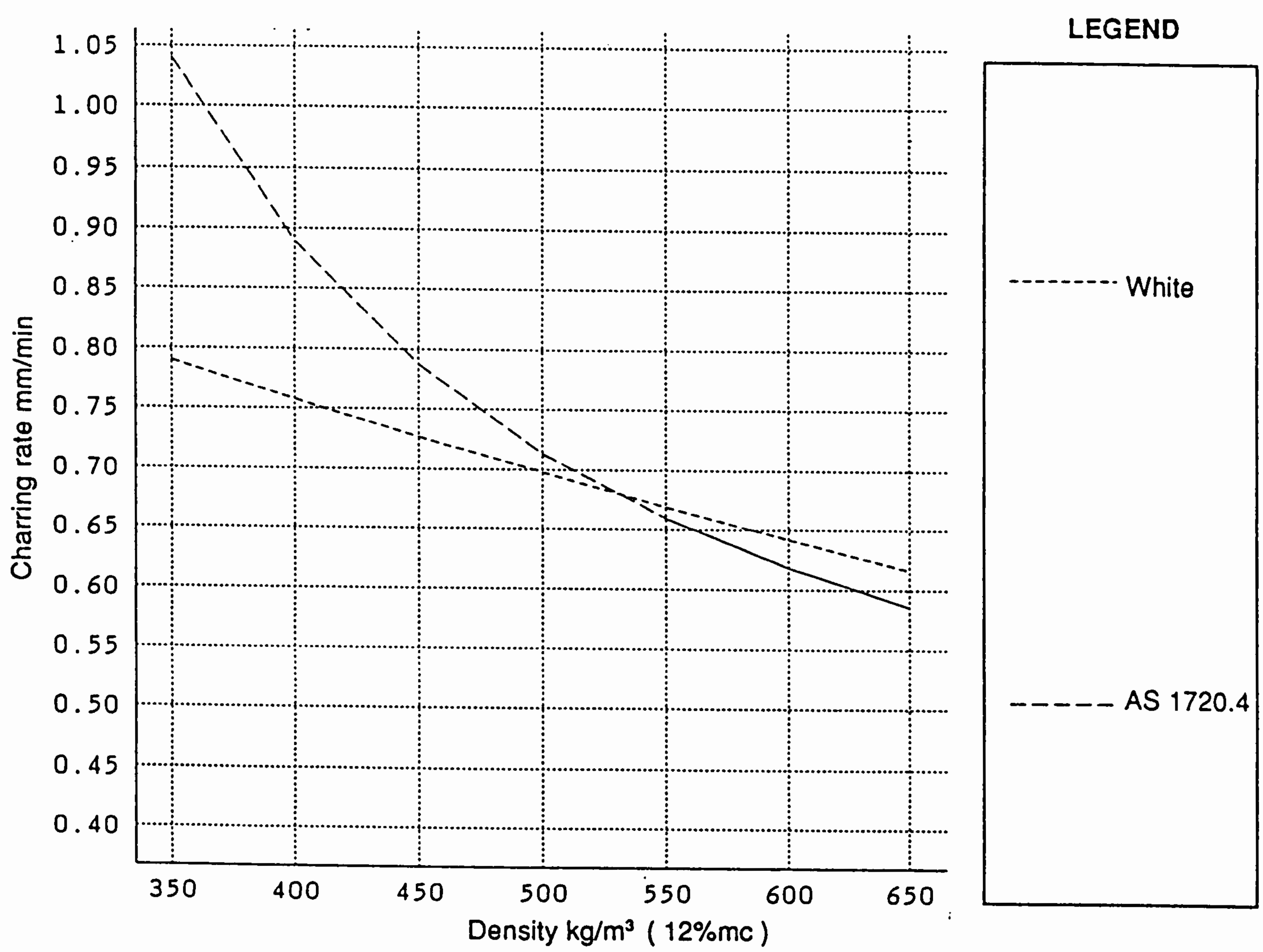


Figure 11 Comparison of charring rate prediction of White's model and AS1720.4

Table 1: Effect of timber moisture content on charring rate

Species *	Charring rate for moisture content of	
	5% mm/min	20% mm/min
Southern pine	0.76	0.71
Douglas fir	0.55	0.45
White oak	0.61	0.52

*density adjusted to 600 kg/m^3

Table 2: Charring Of Timber Samples

Table 2.1

Species	Density oven-dry (kg/m^3)	Moisture Content (%)	Predicted Charring Rate (mm/min)	Actual Charring Rate (mm/min)	Exposure Period (minutes)
Radiata pine	455	0	0.94	0.76	0-29
Radiata pine	621	0	0.80	0.52	0-29
Radiata pine	424	21	0.72	0.67	0-29
Radiata pine	522	14	0.72	0.52	0-29
Radiata pine	565	17	0.67	0.63	0-29
Douglas fir	534	23	0.56	0.55	0-29
Glulam					
Radiata pine (b)	500	12	0.66	0.52	0-29
Radiata pine (a)	500	12	0.66	0.59	0-29
Radiata pine (c)	500	12	0.66	0.59	0-29

(a) exposure parallel to laminates
(b) exposure perpendicular to laminates (200 mm in length)
(c) exposure perpendicular to laminates (100 mm in length)

Table 2.2

Species		Density oven-dry (kg/m^3)	Moisture Content (%)	Predicted Charring Rate (mm/min)	Actual Charring Rate (mm/min)	Exposure Period (minutes)
Radiata pine		409	0	0.77	0.80	0-60
Radiata pine		483	0	0.71	0.72	0-60
Radiata pine	*1	544	0	0.75	0.93	0-60
Douglas fir		372	15	0.65	0.68	0-60
Radiata pine	*4	407	21	0.64	0.60	0-60
Radiata pine		516	16	0.62	0.58	0-60
Radiata pine		522	16	0.62	0.60	0-60
Douglas fir		536	24	0.48	0.48	0-60
Douglas fir	*3	550	16	0.53	0.57	0-60
Radiata pine	*2	620	20	0.53	0.53	0-60
End grain	(d)					
Radiata pine		550	12	0.63	0.60	0-60
Radiata pine		550	12	0.63	0.59	0-60
Radiata pine		550	21	0.56	0.56	0-60
Radiata pine		550	21	0.56	0.56	0-60
CCA treated timber						
Radiata pine H3		550	15	0.61	0.60	0-60
Radiata pine H5	*5	550	13	0.62	0.53	0-60
Glulam						
Radiata pine	*6(c)	500	12	0.57	0.63	0-60
Radiata pine	*7(b)	500	12	0.57	0.57	0-60
Radiata pine	(a)	500	12	0.57	0.62	0-60

(a) exposure parallel to laminates
(b) exposure perpendicular to laminates (200 mm in length)
(c) exposure perpendicular to laminates (100 mm in length)
(d) exposure on end grain
* samples instrumented with two thermocouples at 18 mm and 36 mm depth

Table 2.3

Species	Density oven-dry kg/m^3	Moisture Content %	Predicted Charring Rate mm/min	Actual Charring Rate mm/min	Exposure Period minutes
Radiata pine	504	0	0.88	1.23	31-60
Radiata pine	559	0	0.84	0.84	31-60
Radiata pine	513	21	0.65	0.57	31-60
Douglas fir	523	26	0.53	0.55	31-60
Radiata pine	528	15	0.70	0.74	31-60
Radiata pine	625	19	0.60	0.57	31-60
Glulam					
Radiata pine	(a) 500	12	0.65	0.97	31-60
Radiata pine	(c) 500	12	0.65	0.87	31-60
Radiata pine	(b) 500	12	0.65	0.97	31-60

(a) exposure parallel to laminates
(b) exposure perpendicular to laminates (200 mm in length)
(c) exposure perpendicular to laminates (100 mm in length)

Table 2.4 Charring evaluation of samples instrumented with thermocouples, exposed for 60 minutes.

Sample No	density kg/m^3	moisture content %	mean charring rate mm/min thermocouple at depths of 18 mm	36 mm	charring rate at 1 hour
*1	544	0	0.98	0.92	0.93
*2	620	20	0.45	-	0.53
*3	550	16	0.58	0.61	0.57
*4	407	21	0.49	-	0.60
*5	550	13	0.67	0.61	0.53
*6	500	12	0.73	0.73	0.63
*7	500	12	0.67	0.60	0.57

* samples instrumented with two thermocouples at 18 mm and 36 mm depth

Note - where a charring rate is not shown for the thermocouples at 36 mm, the temperature at that depth had not exceeded 300°C.

Table 3 Charring Of Glulam

Glulam Charring Measurements

Location	Depth of thermocouples (mm)	Charring Rates (mm/min) Mean	Range
Left side	18	0.75	(0.69-0.82)
Right side	18	0.75	(0.73-0.77)
Left side	36	0.68	(0.55-0.80)*
Right side	36	0.87	(0.63-1.04)*
Narrow edge	36	0.75	(0.61-0.86)
Weighted mean for whole of specimen		0.77	(0.55-1.04)

* glue lines represented by upper end of range.

Predicted charring rate 0.76 mm/min, see Appendix 1.

Charring rates of timber

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