BARK/WOOD BOND STRENGTH AND ITS ASSOCIATION WITH MATERIAL AND ENVIRONMENTAL VARIABLES

G. A. Moore

Experimental Scientist
C.S.I.R.O. Division of Forest Research
P.O. Box 4008, Queen Victoria Terrace, ACT, 2600 Australia

and

T. A. McMahon

Professor of Agricultural Engineering
University of Melbourne, Parkville, Victoria, 3052 Australia

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ABSTRACT

Bark/wood bond strength was determined for the following Australian grown species: *Pinus radiata, Eucalyptus obliqua,* and a mixture of *E. viminalis* and *E. rubida.* In addition, sixteen other variables describing tree vigor, drought stress, tree size, and material properties were measured. The experiment was conducted in three seasons, and seasonal variation of bond strength was shown for these species.

Seasonal variation in bond strength was similar to that found by other workers. The sapwood moisture content of the eucalypts had a low variability over the seasons. Correlations were found between bond strength and the material variables for the pines sampled in summer and the eucalypts.

Keywords: Bark/wood bond, seasonal variation, chip/bark segregation.

INTRODUCTION

In Australia and many other countries, there is a growing interest in using previously unutilized portions of trees as a fiber resource for paper pulp and other fiber products. Although a considerable amount of forest residues and small dimension logs exists, presenting this resource to the established mill infrastructure in an acceptable form in terms of both quality and price continues to be a problem.

A successful chip/bark segregation process would allow development of residue and small tree harvesting and transport systems to supply chips of high quality to pulpmills. The advantages of chipping in the forest without prior delimbing and debarking, and the advantages of transporting a bulk solid instead of a number of discrete items, would be realized without substantially affecting chip quality to the pulpmill.

To assist in the development of a chip/bark segregation process suited to Australia's commercial pulpwood species, the bark/wood bond strengths of four groups of trees (*Eucalyptus obliqua,* a "stringybark"; *E. viminalis* and *E. rubida,* both "gum" barks; and two different aged stands of *Pinus radiata*) were measured, and correlations were investigated between bond strength and the following variables: some simple material properties of the wood and bark, some measures of tree vigor, and some environmental variables. The results of these studies are presented in this paper.

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LITERATURE REVIEW

Bark/wood bond strength has been investigated by a number of researchers including Wilcox et al. (1954), Berlyn (1965), Fridley et al. (1970), Miller (1975), Madden (1977), Fiscus et al. (1983) and Einspahr and Harder (1983). These studies had various aims, including the design of shaker clamps for mechanical fruit tree harvesters, devising quick tests for cambial activity, assessing the effect of pre-treatments on the bond strength, and the investigation of debarking and chip/bark segregation processes.

With the exception of those studied by Madden (1977), none of the species investigated have been commercially important to Australia, and the climatic conditions experienced were not usually similar to southern Australia's hot dry summers and cool to mild winters. For these reasons, it was considered important to establish the behavior of bark/wood bond strength under local conditions.

In general, those researchers whose principal concern was with debarking and chip/bark segregation have measured bark/wood bond strength and attempted to correlate this with Julian date or season, information about the tree such as diameter, height of sample, sample aspect, and qualitative information about the tree's physiological state.

Fridley et al. (1970) demonstrated a possible relationship between irrigation and bond strength, but the remainder of the researchers did not report work on tree water relations in their experiments.

Similarly, while the moisture content of the wood and its effect on bond strength was investigated by Miller (1975), this was in relation to material that was dried or had undergone artificial adjustment of moisture content. The moisture content of the wood or bark at the time of felling was not reported in relation to bond strength.

The specific gravity of wood, which is a good indicator of wood's strength (Goggans 1961), has not been reported in conjunction with bark/wood bond strength.

The ratio of dormant-season to growing-season bond strengths ranged from 2:1 for spruce (Berlyn 1965) to 8:1 for hickory (Einspahr and Harder 1983). In these studies the definition of "dormant" was clearcut because of the deciduous nature of the trees or the extreme climatic conditions. Barnett (1973) found complete dormancy to be absent in *P. radiata* in New Zealand. To the authors' knowledge, there are no similar studies on eucalypts. Lack of complete dormancy in the trees under consideration may result in a smaller ratio of highest to lowest bark/wood bond strength being observed. The degree of dormancy was not investigated in this study.

EXPERIMENTAL DESIGN

Four groups of trees were chosen for experimentation. These included *E. obliqua* from a natural forest of about 5,000 ha, in which butt diameters ranged from 150–300 mm. A mixture of *E. viminalis* and *E. rubida* from the same forest and diameter range formed the second group. The third group was of *P. radiata* from a plantation of age 11 years, where canopy closure had not occurred; and the final group was of *P. radiata* from a plantation of age 14 years, which had reached canopy closure and had then had a thinning to about 60% of the original basal area 12 months prior to the first sampling. These forests were located approximately 100 kilometers northwest of Melbourne, Australia.

Data were collected for three different seasons (viz. winter, spring, and summer) for the eucalypts, and for the spring and summer seasons for two age classes of *P. radiata*. Because of bushfires between the spring and summer sampling periods, different forests were sampled for the *P. radiata* groups in the two sampling periods. Although these forests were outwardly similar, it must be assumed that they were not statistically identical because of their different geographical locations and possibly different seed sources. This, however, does not alter the validity of the statistical tests performed on the data. The tests on presumed seasonally invariant characteristics such as oven-dry wood density show the degree to which the forests are statistically similar. With this information (the best that is available on the similarity of the forests), the characteristics that do vary with season may be judged.

Ten trees from each group were selected in each season that the group was sampled. These formed a sample from one particular population. As a result there were 10 populations overall. The forests were divided into a large number of potential sample sites, which were consecutively numbered. The first site number for each sample was selected at random, and subsequent site numbers were determined by adding a fixed increment to the current site number. Ten cores were removed from each tree at 10% height intervals from the base to a top diameter of 15 cm for the eucalypts and 8 cm for the pines, which necessitated felling the trees. The variables measured and the way they were grouped for statistical interpretation are shown in Fig. 1. A schematic diagram of the hierarchy is shown in Fig. 2.

The sample size used was such that for an expected coefficient of variation of the failure stress variable of 15% between-trees and 10% within-trees, the coefficient of variation of the sample mean would be less than 4% (see Balodis and James 1980; Balodis 1981).

DATA COLLECTION

Most of the measurements involved routine procedures and are not described. Pre-dawn xylem water potentials were measured using a pressure chamber as described by Turner (1981). Bark/wood bond measurements were made on cores of 10-mm length by 25-mm diameter (eucalypts) or 15-mm diameter (pines) which were removed from discs by a special coring tool manufactured by Stehle GMBH & Co, West Germany. The wooden end of a core was held in a specially designed clamp, and the bark was sheared from the wood parallel to the grain by a compressive force supplied by a semicircular anvil mounted on the cross-head of an Instron model 1122 testing machine (Fig. 3). A cross-head speed of 20 mm/min was used. A separate experiment conducted prior to this work had shown that the registered peak force at this speed was not significantly different from that at 50 mm/min or 0.5 mm/min. A number of different testing procedures were considered, all of which result in failure of the bond in the shear mode (due to either linear or rotational loading) or in tension. The procedure chosen was thought to be the most appropriate because of the ease of core preparation and testing

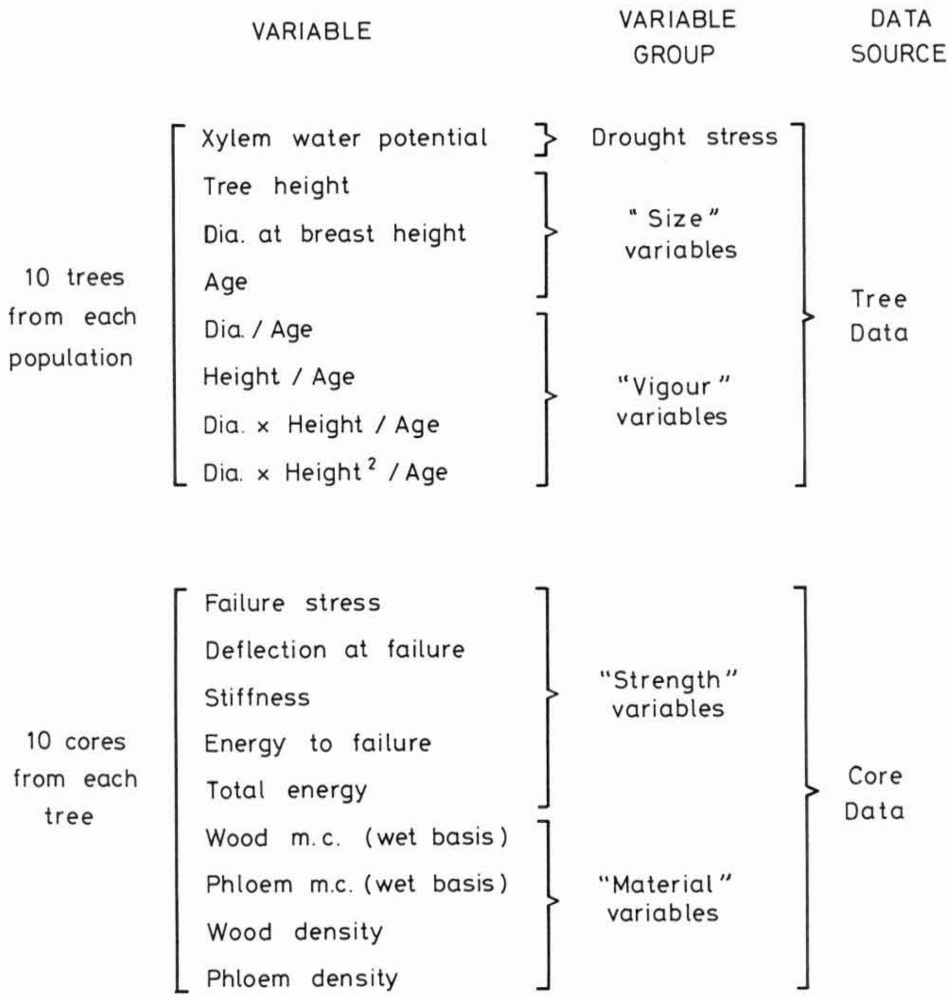

FIG. 1. Measured variables and their groupings.

and the averaging of minute areal irregularities in the bark/wood bond over a relatively large area. A microprocessor-based data logging system was used to gather information from the testing machine.

STATISTICAL ANALYSIS

Means, standard deviations, and coefficients of variation were determined for each variable in each population. There were usually 10 observations for the tree data and 100 observations for the core data in each population. Student's t tests were used to determine seasonal differences in any one group and variable over the seasons. Partitioning of the variance components of failure stress was performed considering the experimental design as being fully nested with repeated subsampling with unequal numbers in the subclasses (Anderson and Bancroft 1952). The sources of variation were: the 3 sesons, the 10 populations as defined earlier, the trees (usually 10) in each population, and the 10 cores from each tree.

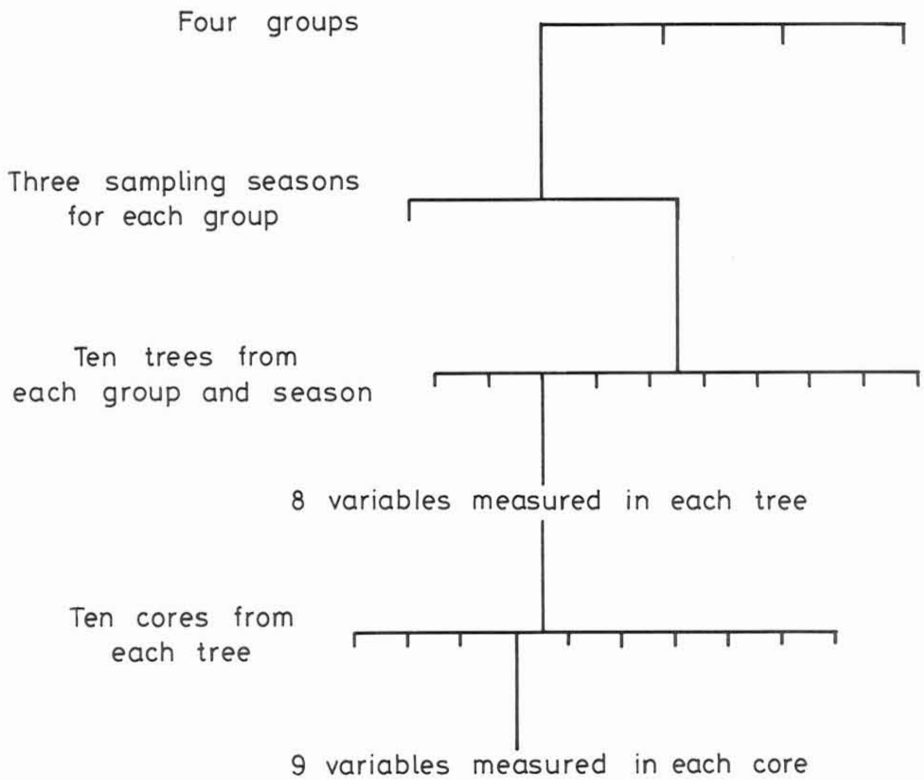

FIG. 2. Schematic of hierarchy.

Between-tree and within-tree coefficients of variation were determined using analysis of variance for the failure stress variable for each population to provide an estimate of the coefficient of variation of the sample means for that variable.

Between-tree correlation matrices for each population were formed for the tree data variables and the tree means of the core data variables. These matrices were used to determine whether some of the populations could be pooled to reduce the number of matrices. For any particular combination of m populations, the matrices of sums and cross-products for each population were added and the pooled correlation matrix formed. The hypotheses H_0: $\rho_{i1k} = \rho \cdot 1k$, H_1: $\rho_{i1k} \neq \rho_{1k}$, where ρ_{i1k} refers to the correlation coefficient of population i ($2 \leq i \leq m$) between failure stress (variable 1) and variable k ($2 \leq k \leq 12$), were tested to determine which of the m populations could be legitimately included in that combination. The method used to test the above hypothesis (Rao 1965) was to take Fisher-z transforms of the correlation coefficients (calculated on n degrees of freedom) for each of the m matrices in the combination and accept H_0 if

$$n - 1 \sum_{i=1}^{m} (z_i - z)^2 < X^2_{m-1}$$

assuming the variance of $(z_i - \bar{z})$ to be $\dfrac{1}{n - 1}$.

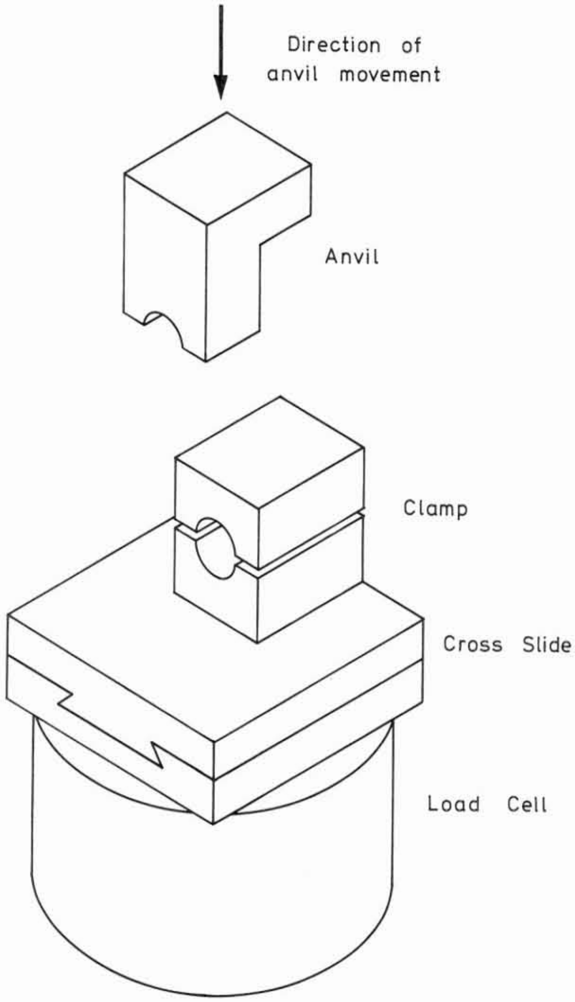

FIG. 3

For each population, the within-tree correlation matrix was formed for the core data variables by first subtracting the tree mean for each variable from each of the cores from that tree and then calculating the correlation coefficients. Also, the data from all of the Eucalyptus cores and all of the Pinus cores were pooled, and the correlation coefficient between failure stress and wood moisture content was calculated for each of these genera.

The pooled between-tree matrices were partitioned as follows,

$$\left|\begin{array}{c|c|c|c} \Sigma_{11} & \Sigma_{12} & \Sigma_{13} & \Sigma_{14} \\ \hline & \Sigma_{22} & & \\ \cline{2-4} & & \Sigma_{33} & \\ \cline{3-4} & & & \Sigma_{44} \end{array}\right| \begin{array}{l} \text{strength variables} \\ \text{material variables} \\ \text{size and vigor variables} \\ \text{drought stress variable} \end{array}$$

TABLE 1. *Population statistics.*

Variable	*E. obliqua*			*E. rubida* and *E. viminalis* mixture			*P. radiata* (old)		*P. radiata* (young)	
	Winter	Spring	Summer	Winter	Spring	Summer	Spring	Summer	Spring	Summer
Failure stress (kPa)	410 (45)	350 (29)	620 (39)	580 (32) b	370 (40)	520 (42) b	210 (41)	290 (37)	200 (29)	250 (33)
Stiffness (N/mm)	237 (44)	318 (39)	391 (54)	270 (29) b	275 (36) b	277 (31) b	28 (32) c	32 (44) c	26 (27) d	28 (52) d
Energy (J)	74 (59)	47 (111)	158 (126)	149 (65) b	55 (71)	146 (112) b	26 (54)	46 (39)	29 (41)	43 (51)
Wood m.c. (wet %)	44.6 (13) a	46.2 (9) a	45.8 (11) a	48.3 (10) b	46.6 (9)	48.5 (8) b	62.0 (6)	60.1 (8)	64.4 (5)	61.9 (6)
Bark m.c. (wet %)	58.3 (5) a	59.5 (5)	57.9 (7) a	61.1 (5) b	61.6 (10) b	61.2 (7) b	73.3 (4)	67.8 (4)	73.9 (4)	71.2 (7)
Wood density (kg/m^3)	621 (12) a	604 (9) a	602 (9) a	566 (9) b	598 (7) b	575 (10) b	417 (13) c	436 (14) c	374 (11)	389 (11)
Height (m)		17.6 (21) a	15.6 (22) a		18.5 (25) b	14.4 (28) b	13.4 (5)	15.3 (11)	8.8 (21)	10.9 (15)
Diameter (cm)		19.3 (24) a	21.3 (22) a		19.7 (30) b	20.0 (21) b	14.7 (9)	15.8 (12)	16.0 (21)	14.9 (20)
Age (years)		46.6 (36) a	47.1 (40) a		41.1 (30) b	36.9 (30) b	14	18	11	12
Vigor ("m^3/year")		151 (41) a	160 (34) a		184 (52) b	171 (53) b	209 (20) c	219 (34) c	225 (58) d	218 (55) d

Figures in brackets are coefficients of variation; same letter in any one line indicates no SD between seasons within species at 1% level (two-sided t test).

TABLE 2. *Analysis of variance of stress data.*

Effect	ndf	Mean square	Partition of variance
Season	2	3,155,500	. . . $96.7\sigma_p^2 + 309.5\sigma_s^2$
Populations	7	1,859,270	. . . $10\sigma_t^2 + 96.7\sigma_p^2$
Trees	87	154,984	$\sigma_c^2 + 10\sigma_t^2$
Cores	873	9,380	σ_c^2

$\sigma_s = 64.7$, $\sigma_p = 132.7$, $\sigma_t = 120.6$, $\sigma_c = 96.8$
n.b. the coefficients of 96.7 and 309.5 arise from some population samples having 9 trees instead of 10.

where the correlation matrix partition Σ_{11} represents the failure stress and failure energy variables, Σ_{22} the moisture content and density variables, Σ_{33} the size and growth rate variables, and Σ_{44} the drought stress variable. For each of the pooled matrices, tests were performed to test the hypothesis, H_o: $\Sigma_{1j} = 0$, H_1: $\Sigma_{1j} \neq 0$, for $j = 2$, 3 or 4, which if accepted indicates that there are no significant correlations between variates 1 and 2, 3 or 4 given that a linear combination of variables within each variate is chosen to maximize the correlation (Morrison 1976a). Where Σ_{1j} was significantly different to zero, canonical correlations were determined for selected models (Morrison 1976b). The percentage of variation explained is indicated by the square of the correlation coefficient.

DISCUSSION

Population statistics

Table 1 shows the population statistics for the experiment. The figures in the brackets are the coefficients of variation of the population and the preceding figures the population means.

The variations of failure stress with season show trends similar to those of other workers (e.g., Einspahr and Harder 1983) who found that the bark/wood bond strength in the spring was lower than the strength in the dormant season (usually winter). However, the magnitude of the variation, less than 2:1 for all groups, was below that found by others (viz. from 2:1, found by Berlyn (1965), up to 8:1, found by Einspahr and Harder (1983)).

The failure stress of the eucalypts was greater than that of the pines, thus supporting the hypothesis of Fiscus et al. (1983) that the bond strength is associated with the presence of fibers in the bark.

The moisture content of the sapwood of the eucalypts showed remarkably low variability with season. Although there are limited data for evergreen hardwoods, research done on softwoods and deciduous hardwoods suggests a significant tissue capacitance exists (e.g., Waring and Running 1978; Chaney 1981).

The between-tree and within-tree coefficients of variation of failure stress ranged from 14% to 37% and from 16% to 35%, respectively. These were larger than anticipated. As a result, the coefficient of variation for the sample means ranged up to 10% instead of the predicted 4%.

The remaining population statistics are basically definitive of the populations and are included for reference.

TABLE 3. *Canonical correlations.*

Data set	Dep. canon. variate	Ind. canonical variate	Correlation coefficient
Eucs	$S - 0.88E$	$\Phi_w - 0.34\Phi_b + 0.75D$	0.64
Pines (summer)	$S - 0.78E$	$0.53\Phi_w - 0.42\Phi_b + D$	0.76
	$0.12S + E$	$0.53\Phi_w - 0.42\Phi_b + D$	0.90
	S	$-0.71\Phi_b + 0.3D$	0.85
	S	$-\Phi_b$	0.80
	E	$-\Phi_b$	0.78

S = failure stress, E = failure energy, D = density, Φ_w = wood moisture content, Φ_b = bark m.c.

The analysis of variance table and partitioning of the variance are shown in Table 2.

Within-tree correlation matrices

Considering the 10 within-tree correlation matrices derived from the core data, of all the linear relationships between any of the strength variables and any of the material variables, no more than 40% of the variation was ever explained by a relationship. The correlation coefficient between failure stress and wood moisture content in the matrix derived from the pooled pine data was the highest where 25% of the variation in failure stress was accounted for by wood moisture content.

Between-tree correlation matrices

The procedure of pooling data sets resulted in three correlation matrices being formed, these being one matrix based on the data from the 6 eucalypt populations, one based on the two populations of pines sampled in summer, and one on the two populations of pines sampled in spring.

Following partitioning, it was found that Σ_{13} and Σ_{14} were never significantly different from zero. Σ_{12} was significantly different from zero in the eucalypts and the pines sampled in summer.

Table 3 shows selected canonical correlation models for the relationship between the strength variables and material variables for two of the pooled populations.

As mentioned earlier, the moisture contents of the eucalypt samples showed little variability with season and as a result only weakly describe the variation in failure stress.

The pines in spring behave similarly to the eucalypts. In the bivariate sense, the correlation coefficient of the moisture content of the bark with failure stress was not significantly different from zero for the eucalypts or the pines sampled in spring.

CONCLUSIONS

The variation of bark/wood bond strength and possible linear correlations between bond strength and a number of material and environmental variables were investigated using a hierarchical experimental design for several important Australian timber species.

The type of seasonal variation was similar to that determined by other researchers, but the magnitude of the variation was smaller. No significant linear correlations were observed between bond strength and the other variables which universally applied for all species and seasons.

The relationship between failure stress and bark moisture content for *P. radiata* in the summer sampling period was relatively strong with 64% of the variability of failure stress being accounted for by bark moisture content.

From a practical viewpoint, only seasonal and species variations in bond strength need be considered in the development of a chip/bark segregation process using chips from freshly felled trees of these species.

Further research into bond strength variation with moisture content changes is required and planned to assess the effect of natural drying on debarking of logs and chips.

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