REMEDIAL TIMBER TREATMENT WITH BORATES

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Abstract - This paper reviews the mode of action, environmental, health and efficacy attributes of borates in remedial timber treatment applications, with an emphasis on the use of disodium octaborate tetrahydrate. It also reviews recent research investigating the important role moisture plays in both borate diffusion and retention in wood. Up to 60 years of global experience and 10 years with remedial application in North America demonstrate that borates offer: proven efficacy against a range of wood-destroying pests; application flexibility; protection that can last as long as the wood remains in service; and a good margin of safety to humans and the environment. Efficacy is broad spectrum and probably via metabolic inhibition.
Key words - Borate, efficacy, leaching, mobility, mode of action

INTRODUCTION

The element boron is ubiquitous in nature where it exists bound to oxygen to form inorganic borates. Examples include boric acid, disodium octaborate tetrahydrate (DOT) and borax. Borates are both essential micronutrients and effective preservatives. Both boron essentiality and toxicity can be considered together as they are likely to result from a similar biological interaction.

ESSENTIALITY AND TOXICITY

The essential element status of boron has been demonstrated for all vascular plants (Gouch and Dugger, 1954; Underwood, 1977; Parr and Loughman, 1983; Dugger, 1983; Lovatt and Dugger, 1984). Schwarz (1974) suggests that, because boron is ubiquitous in animal tissues and possesses properties expected of an essential element, it should be classified under special consideration for trace element function. Other evidence has also suggested that boron has importance in human nutrition, and it has recently been considered to be a probably essential trace element (WHO, 1996). Further information on the importance of boron in animal and human diets has been reported by Hunt (1994) and Nielsen (1994).

One of the essential actions of borates hypothesized in higher plants is metabolic regulation, by virtue of its ability to form complexes with polyols (Figure 1). When the borate ion complexes with compounds that are reactants or products of enzymatic reactions in plants, it may stimulate or inhibit the course of specific metabolic pathways. The effect of boron on the pentose phosphate pathway (Lee and Aronoff, 1967), production of phenolics and lignification (Lewis, 1980; Shorrocks, 1990) is a good example of this. Of course, if intracellular borate concentration is increased to vast excess such metabolic regulation will turn to inhibition which can be deleterious to normal metabolic function. This effect in micro-organisms has been shown to be biostatic rather than biocidal, with these organisms appearing to 'starve' (Cushny, 1940; Goodman and Gillman, 1941; Rosenberg, 1946) if they are not removed from the high boron concentration. The environmental effects of borate have been reviewed extensively (ECETOC, 1996) (Table 2). Boron toxicity to animals and humans has been reviewed; it has been concluded that the tolerable daily intake is 24 mg B/day (IEHR 1995; ECETOC 1995; Murray 1995; WHO, 1998).

Bacteria, fungi and insects are all affected by relatively high concentrations of boron. Because of this boron compounds have been used against bacteria in the form of antiseptics and as preservatives in cos-

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metics and food (Anonymous, 1980). Some species of fungi exhibit effects of boron toxicity, resulting in the aborted growth (Bowen and Gauch, 1966) and in the failure of gametes to cleave. The fungicidal mechanism of action of borates has been investigated and hypothesized that its primary mode of action was on general metabolism by interaction of the borate anion with polyols of biological significance (Figure 1) (Lloyd, 1993; Lloyd, 1995; Lloyd and Dickinson, 1991; Lloyd *et al.*, 1990; Lloyd *et al.*, 1991).

In insects, borate uptake is by ingestion or absorption. Once ingested, borates serve as a slow-acting stomach poison. Exposure to a lethal dose (Table 1) occurs through consumption of borate-treated wood or other substrate, or by insect grooming following contact with DOT dust. Borates can also be absorbed by insects following direct contact when infested wood is drilled and the borate solution is injected under pressure directly into galleries, or when cockroaches, ants and other insect pests come into contact with borate contaminated food residues in cracks and crevices following treatment with a borate spray or dust.

Table 1. Borate efficacy: wood destroying insect pests and decay fungi.

Organism	Wood moisture needs	Boron[1] needed (ppm) to kill	Percent AI[2] in wood
Native subterranean termites	NA	1,000[3]	0.5%
Formosan subterranean termites	NA	2,000[4]	1.0%
Dampwood termites	>20%	1,000	0.5%
Drywood termites	>10%	1,000	0.5%
Lyctid (true powderpost) beetles	>8%	800	0.4%
Anobiid beetles[5]	>15%	800	0.4%
Old house borer larvae[5]	>10%	800	0.4%
Decay fungi	>25%	600	0.3

[1]ppm expressed equals the amount of elemental Boron in the wood after application of DOT. Note: Borates in wood are usually measured in % active ingredient (Ai). Percent ai has been converted to ppm in this chart. However, this conversion has rounded off the actual ppm to whole numbers.
[2]% Ai equals % of DOT in wood.
[3]Requires 1,200 ppm Boron to prevent feeding on wood.
[4]Requires 2,000 ppm Boron to prevent feeding on wood.
[5]1,000-1,900 ppm in pine sapwood prevents attack by first-stage larvae (Taylor, 1967)

WOOD PROTECTION

Borates have been proven effective against all known wood destroying organisms (Carr, 1959; Barnes *et al.*, 1989; Dickinson and Murphy, 1989; Drysdale, 1994; Nunes, 1997; Manser and Lanz, 1998). DOT has been used to protect historic wooden structures and artifacts. (Dickinson, 1996). Remedial treatments with solid boron rods and glycol borates were reported by Bechgaard *et al.*,1979; Dicker *et al.*, 1983; Beauford and Morris, 1986; Beauford *et al.*, 1988; Henningsson *et al.*, 1989).

Borate wood treatment efficacy data has been determined according to European standards under EN 599 (Table 3). In non-termite hazard countries the borate retention requirement is 1 - 2 kg DOT/m^3. For subterranean termite control 5 kg DOT/m^3 is deemed effective. In North America the efficacy of borates against Formosan subterranean termites has been documented by Grace *et al.* (1992, 1994), Anonymous (1993), and Tsunoda *et al.* (1995). Subterranean termite species will not feed extensively on wood containing 1,200 ppm of boron, and Formosan subterranean termites (*Coptotermes formosanus, C. brevis*) will not attack wood having approximately 2,000 ppm boron (Mampe, 1998; Grace, 1997; Scheffrahn, 1998). Carpenter ants (*Camponotus* spp.) are able to detect borate-treated wood and avoid prolonged contact with it.

Table 2. Health and environmental safety margin of disodium octaborate tetrahydrate

Acute oral LD_{50} (rats)	2,550 mg/kg of body weight
Acute dermal LD_{50} (rabbits)	>2,000 mg/kg of body weight
Acute LC_{50} (rats)	>2.0 mg/L
Tolerable Daily Intake (humans)	24 mg B/day
Probable Daily Requirement (humans)	>1 mg B/day
IARC carcinogen	DOT not listed
NTP Biennial Report on Carcinogens	DOT not listed
OSHA carcinogen	DOT not listed
Carcinogenicity/mutagenicity	No evidence in mice (boric acid)
Reproductive/developmental toxicity	High dose animal feeding studies in rats, mice and dogs demonstrated effects. A human occupational study showed no adverse human effect on reproduction. Independent reviews conclude no risk associated with normal handling and use.
Sensitization	DOT is not a skin sensitizer
Eye irritation	Mild eye irritant in rabbits. Not considered a human eye irritant in normal industrial use.
Skin irritation	Non-irritant to intact skin
7-day LC_{50} (Goldfish) *Carassius auratus* (embryo-larval stage)	65 mg B/l (sodium tetraborate)
3-day LC_{50} (Goldfish) *Carassius auratus* (embryo-larval stage)	71 mg B/l (sodium tetraborate)
24-day LC_{50} (Rainbow trout) *S. gairdneri* (embryo-larval stage)	88 mg B/l (sodium tetraborate)
32-day LC_{50} (Rainbow trout) *S. gairdneri* (embryo-larval stage)	54 mg B/l (sodium tetraborate)
96-hour EC_{50} (Green algae) (*Scenedesmus subspicatus*)	24 mg B/l (sodium tetraborate)
24-hour EC_{10} (Daphnids)	
(*Daphnia magna straus*)	242 mg B/l (sodium tetraborate)
Persistent/degradation	Boron is naturally occurring and ubiquitous in the environment, and is dispersed to natural levels through dilution.
Soil mobility	DOT is soluble in water and is leachable through normal soil.
Phytotoxicity	Boron can be harmful to boron sensitive plants at high concentrations. However, boron is an essential micronutrient for healthy plant growth.

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Table 3. Biological reference values for DOT.

Test	Organism	BRV
EN 113	*Coriolus versicolor*	0.76 kg/m^3
EN 113	*Gloeophyllum trabeum*	0.59 kg/m^3
EN 113	*Coniophora puteana*	0.32 kg/m^3
EN 113	*Poria placenta*	0.30 kg/m^3
EN 49-1	*Anobium punctatum* superficial treatment	8.53 g/m^2
EN 49-2	*Anobium punctatum* penetrating treatment	0.30 kg/m^3
EN 47	*Hylotrupes bajulus* penetrating treatment	0.69 kg/m^3
EN 20-1	*Lyctus brunneus* superficial treatment	5.55 g/m^2
EN 20-2	*Lyctus brunneus* penetrating treatment	2.07 (1)* kg/m^3
EN 118	*Reticulitermes santonensis* penetrating treatment	5.55 kg/m^3

*1 kg indicated by other data.

DIFFUSION AND WOOD MOISTURE CONTENT

Borates utilize the natural moisture in the wood to diffuse deeper over time, especially in wood having a moisture level of ≥15 % (Schoeman *et al.*, 1998). Diffusion into wood is dependent upon a number of factors, including the concentration of the borate applied; formulation; the number of treatments; ambient temperature, age of wood, surface condition of the wood, species of wood and moisture content of the wood.

Schoeman *et al.* (1998) reported on the movement of surface-applied borates and wood moisture content (Figure 2). Their study showed rapid penetration of borates within the first week of application, irrespective of initial wood moisture content. However, significant diffusion after one-week post application was only noted in wood having moisture content > 15% on an oven dry weight basis. The study also showed wood moisture content more important than the species of wood. Wood having a low moisture level, (<15%) allows the least diffusion of borates. With a moisture level of < 10% a concentrated layer of borate will be deposited about 3 to 10 mm into the wood, and will deter termite feeding (Williams, 1997). Robinson and Barlow (1995) found that boron treatment to a depth of 2 mm in structural wood provided protection from wood-infesting beetles and that diffusion of large amounts of boron deep into the structural wood is not necessary for protection from initial insect attack or reinfestation.

Williams (1997) reported that subterranean termites feeding on wood with 100 ppm of boron will be killed in 2-4 weeks. Williams and Grace (1997) note that ingestion of boron-tainted food by termite workers, when passed onto other colony members, has the effect of a bait toxicant (see Nunes, 1997). Williams (1997) reported that borates readily diffuse into moist subterranean soil tubes where many individual termites come into contact with boron and are discouraged from building more tubes or feeding.

LEACHING

Borates have frequently been characterized as readily leachable from wood in the presence of water. However, it is more accurate to view the process by which boron is lost from treated timber as diffusion (Lloyd and Manning, 1995). Loss of borate preservatives can only take place when treated timber remains wet throughout its cross section for extensive periods of time, while at the same time having an external sink or destination for boron migration. Lloyd (1995) reported on the reduced rate of boron loss that occurs over time, or rather as the retention becomes too low to continue to drive the diffusion process. This appears to occur well above the toxic limit for many wood destroying organisms, at between 0.2 to 0.4% BAE.

Williams and Mitchoff (1990) observed that borate-treated wood exposed to 360 cm of rainfall was still toxic to termites. Morris and Ingram (1996) reported that after five years of severe exposure, borate-treated western hemlock L-joints (0.2% boric acid equivalent loading of DOT) still retained between 60 to 84 percent of the original borate. After five years of exposure, the mean annual ratings of the borate-treated L-joints also showed no attack and the untreated controls complete failure. Morris and Ingram (1996) reported that one coat of alkyd primer followed by two coats of exterior alkyd paint effectively protected the borate from leaching. Murphy (1998) reported on the outdoor weathering of exposed superficially DOT-treated pine.

Arthur (1967) reported on the long term (5 years) durability of 180 railway sleepers double treated with DOT and 50/50 creosote diesel fuel. These ties were treated by a full cell vacuum pressure process to retentions of the order of 0.7 to 1.7% BAE and were found to contain about 0.3 to 0.5% after the five year ground contact exposure. The rates of boron loss, initially fairly rapid at higher retentions, showed a marked tendency to diminish with time (Figure 3). Analytical tests on wood samples taken from building timber after five years of exposure in Wellington, New Zealand show boron loadings remain at the 0.17 - 0.33% DOT retention, and providing protection against fungal decay and insects (Anonymous, 1994).

Table 4. Borate formulations used in remedial applications.

Formulation	Applications
DOT Solution (10% or 15%)	Applied as a surface spray, as a surface foam, or injected under pressure into pest galleries in wood members as a spray or foam. Primarily targeting dry-wood and subterranean termites, boring beetles and carpenter ants.
Boric Acid and DOT Dust	Applied in attics, in wall voids, in subflooring voids, or in cracks and crevices. Primarily targeting dry-wood termites, carpenter ants and cockroaches.
Glycol Formulations	Applied either diluted as a surface spray to wood surfaces or injected under pressure into pest galleries in wood, or as a concentrate in place of injectable pastes. Primarily targeting dry-wood and subterranean termites, boring beetles and carpenter ants, or decay fungi in the latter application.
Solid Boron Rods	Inserted into exterior or ground contact timbers such as telephone poles, fences, decks, or components in contact with exterior walls or below damp proof course. Provides a reservoir slow boron release. Primarily targeting decay fungi and subterranean termites.
Injectable Pastes	Injected into exterior or ground contact timbers such as telephone poles, fences, decks, or components in contact with exterior walls or below damp proof course. Provides a reservoir slow boron release. Primarily targeting decay fungi and subterranean termites.

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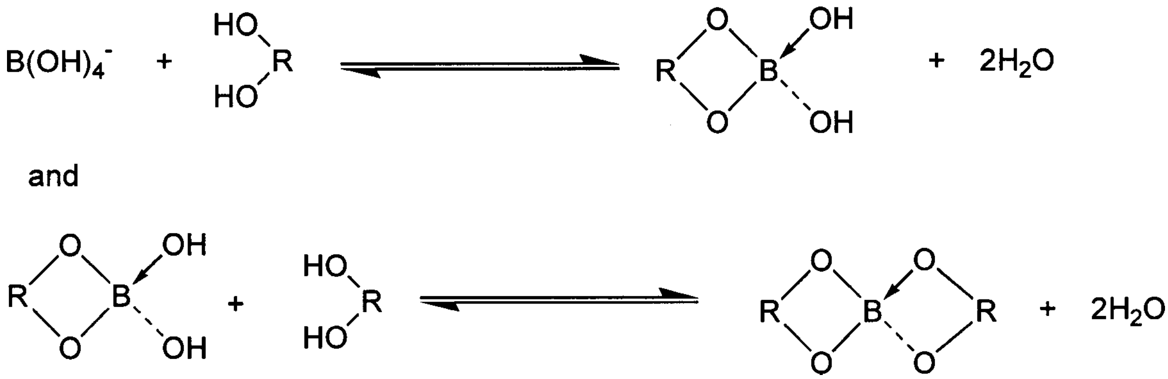

Figure 1. Chelate complex reactions of borate anion (shown) with oxidized co-enzymes probably lead to the biostatic effects of borate through metabolic inhibition.

N.B. complexes are negatively charged and are further stabilized with cationic polyols

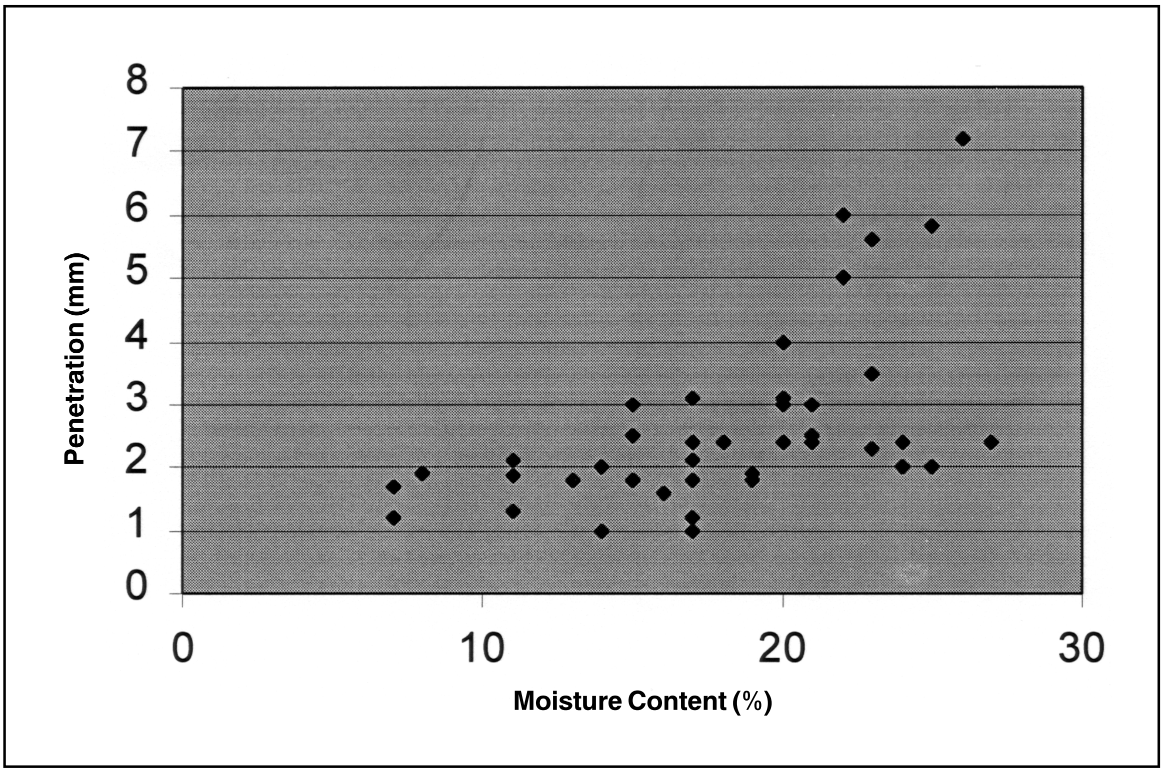

Figure 2. DOT Penetration in six wood species after six months at low moisture contents.

N.B. Penetration determined using curcumin reagent, which shows approximately half the retention gained through analysis. R2 = 0.43 for best fit line plotted for <15% moisture content and R2 = 0.52 for best fit line plotted for >15%.

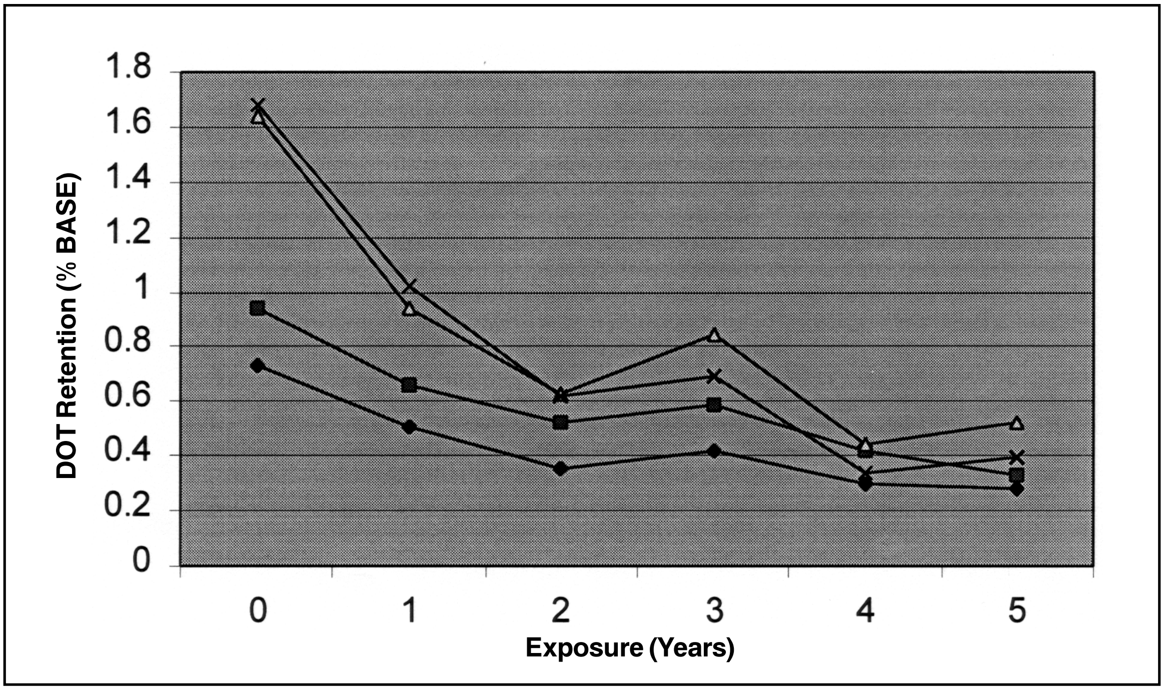

Figure 3. Mean Analytical DOT Retention in Sets of Railway Sleepers Installed in Malaysia.

CONCLUSIONS

Borates are wood preservatives of low mammalian and environmental toxicity. Their action is probably via chelate complex formation with co-enzymes which results in metabolic inhibition. They have found extensive and effective use in remedial timber protection and pest control applications throughout the world. Data shows that concerns regarding the leaching of borates from treated wood has over-stated the risk of boron loss. Borates do not leach out of structural wood under typical conditions and leaching is not a concern for borate-treated structural wood as long as the wood is sheltered from rain or sealed against moisture.

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