Assessing variability in the hygrothermal performance of magnesium oxide (MgO) cladding products of the Australian market

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High humidity causes water absorption in MgO boards with high chloride content.
Chloride concentration determination by EDS is a marker for staining.
Thermal analysis can be used to predict possible water absorption and staining.
There is need for quality control of chloride content and susceptibility to staining.

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Abstract
Magnesium oxide (MgO) boards are relatively new cladding materials on the Australian construction market. They are chosen primarily for their fire resisting properties and are fast replacing traditional cladding materials in newer buildings. Recent reports of water staining on MgO boards is thought to be due to the effects of relative humidity promoting corrosion of metallic fasteners. Different commercially available MgO board samples were investigated by following their behaviour in a controlled relative humidity environment and when in contact with different metallic fasteners. It is observed that water absorption is different for different products and that staining varied with the composition of the metallic fasteners. Staining and water absorption was not a problem at a low relative humidity (RH) of 75% but was evident at a high humidity of 97% for all but one of the MgO board samples. The concentration of chloride is implicated and has its origin in the binder material. These results emphasise the need for standard characterisation of commercially available MgO boards for their use in high humidity environments.

1. Introduction
Magnesium Oxide (MgO) wallboards are an alternative construction material to fibre cement and gypsum sheeting and are a relatively new product on the Australian market. MgO boards are now used in several exterior and interior applications including exterior sheathing, wall and ceiling linings, fascias, and soffits. They are now widely distributed as prefabricated wall systems [1]. MgO products are selected for their fire resistance, strength, resistance to mould and mildew, and have a lower environmental footprint [2–5].

The product is widely used throughout Europe and Asia. Recent reports [6–8] from Denmark on the use of MgO wall boards in new buildings have detailed the effect of high relative humidity on damage from excessive dampness leading to accelerated corrosion of contacting metal fixtures. The hygroscopic nature of the board promoted these effects. MgO boards are chosen for their superior fire rating and have continued to be used with little consideration of the possible adverse effects of humidity on their functional performance. Similar damage from use of magnesium oxide wallboards as green construction materials is reported to have affected many homes that now require expensive replacements [9].

Hygrothermal damage of solid masonry facades has been a source of concern in Australia and elsewhere [10–14]. These failures raise questions about the appropriateness of magnesium oxide boards for the Australian market. Several MgO cladding products are now available in Australia, and while these products have passed current certification procedures (which does not include environmental moisture absorption), there have been no studies of their hygrothermic resistance. The present study has investigated five different magnesium oxide panels available on the Australian market and the likelihood of these products being...
susceptible to hygrothermic failures associated with excessive moisture absorption and corrosion. Based on this data, the variability in quality between different magnesium oxide wallboard products can be assessed and their suitability for use in different regions of Australia determined.

2. Commercially available MgO boards

Commercially available MgO board for construction consist of magnesium oxide, magnesium chloride and inorganic fillers such as sand and perlite. Though specific compositions remain proprietary to different suppliers, they generally consist of:

- MgO 48–52%
- MgCl₂ 22–26%
- Wood fibre 10–12%
- Perlite 10–12%
- Other 2–5%

This variety would be expected to correlate with considerable variability in functional performance. The physical properties of MgO board rely heavily on the cementing action of the magnesium oxychloride (MOC) that is formed in the chemical reaction between MgO and MgCl₂ during processing. The ability of MOC to consolidate filler materials (Sorel cement) has long been recognised as an environmentally acceptable alternative to Portland cement [15,16]. The environmental benefits favouring [17] the use of MOC binder in construction materials is responsible for the reputation of MgO board as a green construction material. The binding phase depends on mole ratios of reactants and the processing conditions. Binder phases, 2, 3, 5 and 9 with distinct chemical and physical identities have been proposed [18,19].

Commercially available MgO boards therefore come with significant chemical diversity dependent on the binding phase dominant in the MOC binding action. The use of thermodynamic data suggests [20] phases 3 and 5 are the most stable in MOC bound materials processed at ambient temperatures. The chemical reactions for phase 3 and 5 are [19]:

Phase 3: \( 3\text{MgO} + \text{MgCl}_2 + 11\text{H}_2\text{O} \rightarrow 3\text{Mg(OH)}_3 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O} \)

Phase 5: \( 5\text{MgO} + \text{MgCl}_2 + 13\text{H}_2\text{O} \rightarrow 5\text{Mg(OH)}_3 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O} \)

Though phase 3 is thought [19] to be the key binding phase in commercially available MgO boards, other phases in different proportion are known to be present in MOC consolidated products. Additionally, the actual stoichiometry of the hydration is a subject of disagreement in the literature. Free chloride has been implicated in many reports of hygrothermal damage [6,7]. The uncertain composition of the binding phase coupled with the doubtful stoichiometry of hydrating water exacerbates the variability of products and consequently overall hygrothermal performance. There are currently no codes specifying these chemical parameters and there are no tests specifying the hygrothermal performance rating of MgO construction boards, but reports of damage continues. Humidity in the coastal cities of Australia can reach over 90% for sustained periods and it is therefore important to assess the range of MgO products and how well they perform as external and internal construction materials under conditions of high humidity.

3. Experimental methods

3.1. Board samples

Five samples of MgO boards from various sources and a fibre cement (FC) board for comparison were investigated for water absorption and staining when in contact with metallic fasteners. The boards as-supplied were labelled:

- Sample A 10 mm MgO board from source 1
- Sample B 10 mm MgO board from source 2
- Sample C 10 mm MgO board from source 3
- Sample D 10 mm MgO board from source 4
- Sample E 8 mm Fibre Cement (FC) board
- Sample F 12 mm MgO board from source 5

3.2. Water absorption in ambient and controlled humidity

The five board samples of MgO and FC were cut into 40 mm × 40 mm test samples. The edges were sealed by epoxy resin to limit absorption effects to the surfaces only.

Samples were dried in an oven maintained at 90 ± 5 °C until constant weight was achieved to remove pre-existing moisture. Previous studies [6,8] suggested that the threshold for excessive moisture absorption in MgO boards was 84% RH. Two RH levels at 75% (below the published threshold) and 97% (above published threshold) were used. These two RH levels were achieved in a 3.5L sealed, transparent container using saturated salts with known [21] equilibrium RH values of 97.0 ± 0.4% (potassium sulphate) and 75.1 ± 0.2% (sodium chloride) at 30 °C (Fig. 1).

As the chamber volume was relatively large (3.5L) to accommodate the test sample configuration, a fan with a microcontroller was programmed to periodically circulate the air and maintain near constant humidity. The relative humidity (RH) and temperature data were collected via a DHT22 temperature humidity sensor and was recorded with a data acquisition system as illustrated in Fig. 1. The samples were exposed to the controlled humidity environments and the resultant mass change monitored over 90 days.

3.3. Fastener corrosion tests

The fastener corrosion investigation evaluated the susceptibility to corrosion of standard fastener screws connected to a mild steel section typically used with MgO cladding. Based on the results of the water absorption tests, three MgO board and the fibre board samples were selected for fastener corrosion tests in the controlled humidity chamber. Two 300 mm × 40 mm strips from each board were prepared, one sample used for analysis of fastener corrosion when in contact with board alone, and the second fastened to a 40 mm × 40 mm × 300 mm square steel section as illustrated in Fig. 2.

Five commonly used fastener types (details on Table 1) were selected for analysis. The section surface of the steel was sand blasted to remove oxide layer and then cleaned with water at 60 °C after which it was blown to dry in a hot air stream.

Fasteners were installed using the standard installation procedures for MgO cladding. The fasteners were staggered as illustrated in Fig. 2a to reduce the likelihood of the MgO board splitting. Test samples were placed with sufficient space for air flow across all components. The environmental chamber was maintained at 32 ± 2 °C, in accordance with ASTM A90/A90M specifications. The chamber remained closed for the duration of the experiment, apart from interruptions of less than 10 min for inspection and replenishment of the saturated salt solution, with a maximum of one inspection per day. The test was conducted for 94 days.

After visual inspection of the samples, the fasteners were removed from the MgO board samples and corrosion products characterised by Scanning electron microscopy (SEM) and Energy Dispersive Spectroscopy (EDS).
3.4 Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analyses

SEM/EDS examination of board samples was employed to monitor compositional variations in board samples and corrosion products from exposed metallic fasteners. Small samples of MgO boards were mounted on aluminium stubs with double-sided carbon tape. The board samples were gold coated using an argon ion sputter coater for electrical conductivity measurements. Both the cross-sectional area and the surface of the boards were examined. The edges of the fasteners screws were probed with EDS to monitor corrosion products. The SEM was operated at an accelerating voltage of 30 kV.

3.5 Thermal analyses

Thermal analyses were conducted on a simultaneous thermal analyser (STA) to follow the thermal events that represent release of absorbed water and structural decomposition. A small quantity of each board was ground into powder and about 50 mg of this powder loaded into an alumina pan. A thermal scan was conducted at a scanning rate of 20°C/min from room temperature to 800°C. The STA was programmed to collect data for differential scanning calorimetry (DSC) and Thermo-gravimetry (TGA). The TGA data were used to follow mass loss that can distinguish between absorbed water and volatiles released from structural decomposition.

4. Results

4.1 Moisture absorption in controlled humidity

Water absorption represented by mass gain for different boards is presented in Figs. 3 and 4 for controlled humidity of 75% and 97% RH, respectively. Mass gains for all samples exposed to the 75% RH atmosphere very quickly approached saturation with maximum mass gains of 4–11%. These maximum mass gains varied between MgO boards, but MgO board F appeared to give the best hygroscopic performance with a maximum mass gain of 4.5%, comparable to the value 3.2% recorded for the traditional FC board.

The water absorption results for boards exposed to 97% RH are shown in Fig. 4. All MgO samples except sample F experienced mass gains greater than 20% and these gains were still increasing after 55 days for MgO samples A B and D.

These results indicate that at a relatively low humidity of 75% RH, hygroscopic water absorption doesn’t cause long-term damage to MgO boards. However, the large water absorption recorded for samples exposed to a RH level of 97% indicates that these boards are prone to hygrothermal damage. The weight gains in the sample boards after 55 days were compared for the two test RH levels (75 and 97%) in Fig. 5. All samples, including the FC board sample, had a greater mass increase after 55 days exposed to 97% RH, compared to 75% RH. At 75% RH, the increase in mass was less than 11% for all boards, although MgO board F and FC (board E) both had less than 5% weight gain. It is clear that water absorption should pose no problem at relatively low humidity. MgO boards C and D absorbed...
twice as much moisture when exposed to 97% RH, relative to 75% RH.

When exposed to the 97% RH environment, both MgO samples C and D showed condensation as “teardrops”, suspected to be salt solution emanating from dissolution of chloride. Sample C, in particular, had clear teardrop leachate by the 20th day, whereas tear-drops were observed after 41 days on sample D. This is consistent with the approach to saturation results represented in Fig. 4. Sample C approached saturation by the 20th day while sample D still continued to absorb water. The leaching observed from MgO board C is shown in Fig. 6. Leaching occurred when the sample achieved saturation. No leaching was observed for any sample exposed to the 75% RH environment. It is clear that the different MgO boards behaved differently on exposure to the high humidity (RH = 97%) environment.

A comparison of the percentage mass increase after 55 days (Fig. 5) demonstrated the variability of the samples. MgO samples C and D experienced the largest mass increase of approximately
26.5% and 30.0% respectively at 97% RH. MgO samples A and B experienced slightly smaller mass gains of 23.6% and 20.9% respectively. MgO sample F had the lowest mass gain of 11.9% which was closest to the performance of the traditional FC board sample which had a mass gain of 7%.

MgO Sample F exhibited the best performance of the MgO board samples tested when exposed to a high humidity environment, comparable to regular FC board. Previous studies [6,7] of hygrothermic damage to commercial MgO board implied the damaging role of free chloride in promoting water absorption and subsequent damage. EDS analysis was therefore used to quantify chloride concentration in the sample boards.

4.2. Measuring chloride content by SEM/EDS analysis

The corrosion associated with MgO boards has been correlated with the presence of magnesium oxychloride [6,8,14,22] and so the intention of the energy dispersive X-ray spectroscopy (EDS) analysis of MgO boards was to probe the different samples for the presence of chloride and make a comparative evaluation of the concentrations variations in the samples.

4.3. Observation of fastener corrosion

MgO samples A, B, and F were chosen for investigation of the effect of high humidity on fastener corrosion. Two sets of
observations are reported in Table 4: (i) screw fasteners in board alone, and (ii) screw fasteners securing board to a steel section.

Images of the screws used to fasten MgO board B to steel are shown in Fig. 7. The stainless steel (SS) screws 304 and 316 did not show any visible sign of corrosion, while other screws were severely corroded as shown on Fig. 7. Fig. 8 shows the conditions of Zn plated screws used to fasten board B (SC) and MgO board F (NC) to the steel section. This emphasises the quality difference between MgO boards B and F for which the fastening screws were respectively observed (Table 4) to be SC and NC.

From Fig. 7, and Table 4, it is evident that commonly used non-stainless, coated or galvanised steel fasteners are not suitable for most MgO boards and that chloride concentration correlates with corrosion. The corrosion of screws increased when MgO samples were fastened directly to steel. Fig. 9 shows the condition of a gold passivated screw in board only which exhibited only mild corrosion, and in board fastened to steel which showed severe corrosion and leaching. A cross section of leaching from the coated screw in board B fastened to steel is shown in Fig. 10. This experiment emphasises the acceleration of corrosion when MgO boards are fastened to metal, which is the current practice in boarding and board framing. The electrical contact of two dissimilar metals promotes electrochemical corrosion and consequent leaching. The implication is that when MgO boards are fastened to other metallic components in a frame or structural component, the susceptibility for hygrothermic damage increases.

The leaching evident for sample B accelerates the corrosion of fasteners. A comparison of gold passivated fasteners in MgO board B demonstrates the corrosive nature of the leachate and the effects on contacting fixtures.

4.4. SEM/EDS analysis of corroded screw fasteners

The screws used in the exposure tests were examined by SEM/EDS to follow the corrosion process. Fig. 11 shows the surface condition of screw threads for screws used to fasten MgO board B to a steel section after exposure to high humidity. EDS investigation of the corrosion debris (Fig. 11a) indicated that it was composed

<table>
<thead>
<tr>
<th>Screw Type</th>
<th>Screw in Board only</th>
<th>Screw in Board fasten to steel section</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>MgO-A</td>
<td>MgO-B</td>
</tr>
<tr>
<td>Gold passivated</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>Galvanised I</td>
<td>NC</td>
<td>M</td>
</tr>
<tr>
<td>Galvanised II</td>
<td>NC</td>
<td>M</td>
</tr>
<tr>
<td>Zinc plated</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>304SS</td>
<td>NC</td>
<td>NC</td>
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<tr>
<td>316SS</td>
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*NC: No visible corrosion, L: Low corrosion, M: Medium corrosion, S: Severe corrosion

Fig. 7. Conditions of screws attached to MgO board B fastened to a steel section (i) 316SS, (ii) 304SS, (iii) Zinc Plated, (iv) Galvanised I, (v) Galvanised II, (vi) Gold passivated.

Fig. 8. Variability of MgO boards on corrosion of zinc plated fastening screws (a) MgO board F (b) MgO board B.
mainly of Fe and Zn oxides. The strong Fe and Cl signals in the EDS spectrum confirmed that the protective Zn coating of the screw did not survive the corrosive chloride environment originating from the board exposure to high humidity. In the case of stainless-steel screw 316 SS, the SEM image (Fig. 11b) and EDS spectrum indicated a clear screw edge with no chloride containing debris, despite exposure to the relatively high chloride content of MgO board B. This observation confirms that stainless steel screws are a good choice for fasteners of MgO boards. However, it is important to add that in the long term, the electrical contact of stainless steel with a less noble framing metal could lead to corrosion of the latter.

Fig. 8 shows the general appearance of Zn coated screws in board F and B. EDS probing of the screw surfaces was used to confirm the effects of the board on screw corrosion after exposure to a high humidity atmosphere. Figs. 12 and 13 compare the EDS spectra of Zn coated screw in MgO boards B and F. The screw through board B showed clear evidence of corrosion with strong peaks for Fe and Cl in the EDS spectrum of the screw edge. The strong Fe line (Fig. 12) is an indication that the protective Zn coating on the screw was fully removed by oxidation. However, the screw in board F was clean and showed no evidence of corrosion. The EDS spectrum (Fig. 13) contained a small Fe signal from the edge of this screw and a strong Zn signal, indicating that the Zn protective coating was still intact.

4.5. Thermal analyses

The Thermo-gravimetry analyses (TGA) signatures for all of the sample MgO and fibre boards are shown in Fig. 14. Gradual mass loss up to about 300 °C is indicative of absorbed water in the sample. The sharp and relatively large mass loss that accompanied the TGA of all samples in the temperature range 300–420 °C represents the loss of structural water in the binder phases. The mass loss with temperature stabilised for both MgO sample F and Fibre board sample E just at about 200 °C while other MgO samples continued
to gradually loose mass before a sharp change soon after 300 °C. Moreover, MgO board F showed a significantly lower water mass loss in comparison to other MgO samples. Overall, the TGA signatures indicate that MgO board F contained significantly less absorbed water.

5. Discussion

We have observed significant variation in the quality of MgO board samples from different sources. All the MgO boards tested were prone to hygrothermal damage, with one more resistant to such damage than the others. MgO sample F performed similarly to FC board in terms of moisture absorption and promoting corrosion of contacting metallic fasteners. We attribute this to the difference in composition of this board which did not contain chloride ions.

MgO sample A caused only mild corrosion of the gold passivated and zinc plated fasteners and this observation is attributed to the relatively low chloride concentration in this board. Interestingly, no evidence of leaching was observed with Sample A, but significant moisture absorption still occurred, which created a suitable environment for mild chloride induced corrosion.

MgO samples B, C, and D caused accelerated corrosion of contacting metal fixtures. These MgO boards absorbed significant
amounts of moisture when exposed to high humidity environments. This resulted in leachate containing chloride ions. Severe corrosion of fasteners used with MgO B was the result of high chloride content in this board. MgO samples C and D both exhibited higher moisture absorption than MgO sample B, leading to leaching. The high corrosion and leaching susceptibility of MgO boards B, C, and D renders these boards unsuitable for use as a construction material in environments with a high relative humidity such as northern, coastal Australia.

The origin of chloride induced water absorption can be traced to the nature of the binder phase, MOC. The nature of MOC phases are known to give different thermal signatures in thermogravimetric analysis [19]. The thermal signatures of each samples was investigated with a simultaneous thermal analyser (STA) (Fig. 14). These analyses revealed large mass losses in the TGA profiles attributed to structural hydration loss. All samples showed gradual weight losses from absorbed water consistent with the observed water absorption by MgO samples A, B, C, and D in Figs. 3 and 4. The TGA profile of MgO board F indicated a decreased weight loss relative to the other MgO samples and similar to that of FC board. It appears, therefore, that weight loss observed by TGA analysis correlates with hygroscopicity and could be a relatively simple test for the suitability of MgO products for use in humid climates.

The influence of MOC is consistent with the findings of other studies [6–8,23]. MOC is a hygroscopic material, and the proportion of the MOC phase in a consolidated MgO material may be responsible for the different hygrothermal and corrosion effects observed. Our elemental composition analysis found that all MgO boards other than sample F contained chloride, which would likely be introduced as MOC into the composite. MgO sample F performed similarly to FC board in the high humidity environment. Other MgO samples containing varying volume proportions of MOC ultimately lead to leaching and corrosion of metal fixtures. Based on these results, damage due to dampness of the boards may be attributed to the presence of MOC and its hygroscopic nature. This explanation is consistent with the various levels of chloride observed by EDS analysis of the boards. Damage due to dampness and corrosion may be attributed to the MOC binder used in MgO boards, which leads to chloride containing leachate and corrosion of metallic fasteners.

MgO boards are known to absorb excessive moisture at humidity levels greater than 84% RH and the pores containing magnesium chloride will not dry at relative humidities above 32% RH. The Australian Bureau of Metrology [24] indicates that a majority of Australia has an average relative humidity greater than 70%, with significant portions greater than this 84% threshold. The case can then be made that the use of MgO board formulations with high chloride concentrations in the Australian environment would likely result in failures due to dampness and corrosion.

6. Conclusion

We have observed significant variance in the quality of magnesium oxide boards available for construction in the Australian market. Reports of damage such as dampness and accelerated corrosion of metallic fasteners can be attributed to the hygroscopic nature of magnesium oxychloride, which is used as the binder in many MgO boards. High chloride concentrations in the binders are prone to absorbing water at high relative humidities and may lead to chloride containing leachate. These leachates can attack non-stainless-steel fasteners and teardrop formation itself creates problems even in the absence of ferrous fasteners. There is therefore a need for an industry-based system to classify and categorise commercially available MgO boards into those that will not degrade in high RH environments.

The thermal signature of MgO boards provided by TGA and the monitoring of chloride by, for example, SEM/EDS are possible methods for identifying MgO board types that would perform well in high humidity and be less susceptible to hygrothermal damage.

Conflict of interest

None.
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