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ORIGINAL ARTICLE

Phosphate bonded wood composite products from invasive *Acacia* trees occurring on the Cape Coastal plains of South Africa

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Abstract The feasibility of manufacturing phosphate bonded wood composite board products from four locally occurring invasive acacia tree species (*Acacia cyclops, A. saligna, A. mearnsii* and *A. longifolia*) was studied using a formulated magnesium oxide (MgO) and monopotassium phosphate (KH_2PO_4) binder system. The optimization for the manufacturing process was studied using a central composite statistical design, whereupon the following factors were considered, i.e. KH_2PO_4: MgO ratio, the fly ash content as partial replacement for the binder and the wood content as a ratio of wood to the total inorganic content. A fitted response surface plot was used to show the effect of the main factors and their interactions on the measured board properties. A response surface model was developed to predict the parameters leading to the best board properties. All physical properties evaluated met or exceeded the minimum requirements for low density particleboards. The results showed that the variables considered have significant effects on the physical properties of the boards. The optimum composite manufacturing process for making durable products within the scope of the studied species was found to be a KH_2PO_4/MgO ratio of 1.66, an ash content of 2.7% and a wood/inorganic ratio of 0.96 for the selected wood species.

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1 Introduction

This study describes an assessment of potentially exploiting the woody biomass of invasive Australian wattle species occurring in the areas of the Eastern and Western Cape, South Africa for particleboard manufacturing. A review of plant invasions in South Africa suggests that invaders, such as acacias act as ecosystem engineers by rapidly changing disturbance regimes (Richardson and Wilgen 2004). Such changes can alter the flow and availability of nutrients, living space, sediment, light and water (Macdonald 1986; Gorgens and Wilgen 2004). In South Africa, the environmental management of these invasive species, which focuses on harvesting based eradication, has resulted in the generation of wood waste, as the trees are typically harvested before they reach merchantable size. According to Theron et al. (2004), the total green woody biomass with a minimum diameter of 25 mm is about 10 million tonnes, which covers an area of more than 100,000 ha. This suggests a substantial quantity of raw materials that can be used for wood composite manufacturing.

Conventional wood-based composite products are made with a thermosetting or heat-curing adhesive. Thermoplastics and inorganic binders are used to manufacture wood plastic and inorganic bonded wood products respectively (Youngquist 1999; Irle et al. 2013). These adhesives are chosen based upon their suitability for the particular product and consumer specifications. In the context of a competitive wood composite market, the development of affordable panels with a low carbon footprint is of significant importance. The innovative phosphate binder used in concrete repairs and civil engineering has found increasing application in other fields of manufacturing, including the composite panel industry.

Phosphate binder is made from an acid–base reaction between an acidic phosphate and an alkali base. According to Wagh (2004), the reaction is highly exothermic and the binder sets within minutes into a rigid mass that can be referred to as chemically bonded phosphate ceramic (CBPC). Phosphate bonded composite products are light, durable, moisture resistant and possess good flexural and compressive strength properties (Donahue and Aro 2010). The phosphate based binder is an environmentally friendly material as it contains major elements also used as plant fertilizers, i.e. potassium (K) and phosphorus (P), thus displaced products may enrich the soil nutrients (Laufenberg and Aro 2004).

In order for the proposed products to attain consumer acceptance, standards and command a market premium, a manufacturing process optimization is imperative. Studies have shown that wood and other materials can be bonded with the magnesium phosphate cement (MPC) binder to produce panels with a comparative advantage compared to Portland cement and polymer resin (Jeong and Wagh 2002; Donahue and Aro 2010; Colorado et al. 2011; Wagh 2013). However, very few studies have been conducted on the process optimization of the phosphate based binder in wood composite panels. Ibrahim et al. (2011) optimised the process conditions for encapsulating lead battery waste. The authors reported that a minimum porosity was achieved by using a molar ratio of Mg:K of 1:1, and that a pressing time of 10 min was sufficient to reach compacts of low permeability. Chi and Englund (2014) studied the alkalinity, workability and fluidity of binder ratios and MPC formulations. Using a pull-out test procedure to evaluate the interfacial properties between MPC and sugar maple, a 3:1 weight ratio of KH_2PO_4 and MgO was found to have the best performance (Chi and Englund 2014). Formosa et al. (2015) optimized the process for manufacturing MPC using MgO-containing by-products as raw materials and boric acid as additives to obtain good mechanical properties and proper setting times.

The benefits of MPC bonded wood products as a green building material can be enhanced with the addition of fly ash from coal based energy generation. Fly ash increases durability and strength in chemically bonded phosphate ceramics, improves workability of MPC paste, lowers the heat of the acid–base reaction and increases the total binder content (Laufenberg and Aro 2004; Wagh 2013). The objective of this study was to produce green building panels utilizing wood waste and eco-friendly materials with a low carbon footprint. Board composition, i.e. binder ratio, fly ash and wood content was optimized at laboratory scale to achieve the desired properties.

2 Materials

2.1 Wood species

The selected tree species used in this study were Black wattle (*Acacia mearnsii*), Long-leaved wattle (*A. longifolia*), Port Jackson (*A. saligna*) and Rooikrans (*A. cyclops*). These species were supplied by EC Biomass Fuel Pellets (Pty) Ltd, Port Elizabeth, South Africa. The trees were harvested in the Green bushes area in Port Elizabeth, and the wood was supplied as wood waste from processed logs. The Black wattle was about 6 years old while the other acacia species were about 3 years old at the time of harvest.

2.2 Magnesium oxide

The magnesium oxide was MAGOXBPPO, a heavy magnesium oxide from Macco Organiques, Zahradnl, Czech Republic with the following composition: assay 96% min; calcium $<1.1\%$; iron $<0.05\%$; acid insoluble substances $<0.1\%$; free alkali and soluble salts $<2.0\%$, heavy metals $<0.002\%$; arsenic $<0.0003\%$; loss on ignition $<10.0\%$ and bulk density (loose) 400–600 g/l.

2.3 Monopotassium phosphate

Monopotassium phosphate is commonly used as plant fertilizer and as a food ingredient (salt). For this project, MKP 0-52-34, a white crystalline product was purchased from Shijiazhuang Lvhe Fertilizer Technologies Co. Ltd, China. It had the following composition: $KH_2PO_4 > 98\%$; $P_2O_5 > 51.2\%$; $K_2O > 33.5\%$; chloride $<0.2\%$; water insoluble $<0.2\%$; moisture $<1.0\%$ and pH 4.3–4.7. Wagh (2004) reports that acid phosphates with a P_2O_5 content of 50–60% may be suitable for the production of chemically bonded phosphate ceramics.

2.4 Fly ash

Fly ash was obtained from Ulula Ash, South Africa and complies to the SANS 50450-1:2011 class S specification. Class S Fly ash (SFA) is an ultra-fine, powdery residue obtained from coal fired power plants and it is a South African Bureau of Standards (SABS) approved product. It is of structural concrete grade, finer than cement and is used as a partial replacement for cement. It had the following composition: $SiO_2 < 60\%$; $Al_2O_3 < 35\%$; $CaO < 10\%$; $MgO < 5\%$; $Fe_2O_3 < 5\%$; $TiO_2 < 5\%$.

3 Methods

3.1 Wood preparation

The wood residue was hammer milled and sieved through a 1 mm sieving slice. The differences in the particle distribution were not considered in this study since the aim was to simulate an industrial wood milling process. The resultant wood particles were conditioned at 20 °C and 65% RH for 96 h. The equilibrium moisture content of the material was found to be 7%.

3.2 Board formation

The materials were mixed thoroughly according to Table 1. The amount of water added was based upon formulation using the formula.

$$W = B + (FSP - MC) \times F$$

W = amount of water (ml), B = amount of inorganic components (g), FSP = fibre saturation point (%), MC = moisture content of fibre (%), F = amount of fibre (g)

The pre-calculated amount of water was added to the materials and the mixture was stirred. The paste was poured into a steel mould measuring 218 × 77 × 40 mm^3 and a steel bar 27 mm thick was placed on the slurry to fit into the mould. The set-up was transferred to the laboratory press and a pressure of 200 KPa was applied for 5 min at room temperature. Thereafter, the mould was removed from the press and the board was demoulded. The same procedure was repeated for all wood species. The formed boards were allowed to air-cure in the laboratory for 24 h. Thereafter, they were conditioned at 20 °C and 65% RH for 96 h before testing.

Table 1 Factors and corresponding levels for response surface design

Factors	Level		
	Low	Medium	High
KH_2PO_4/MgO	2	3	4
Fly ash (%)	0	0.1	0.2
Wood/inorganic	0.63	0.75	0.88

3.3 Testing

Testing of the boards was carried out according to ASTM Standards D1037-99 (ASTM 1999). The properties evaluated include density, modulus of rupture (MOR), modulus of elasticity (MOE), water absorption (WA), and thickness/volume swelling (TS/VS). The sorption tests were determined after 24 h immersion in distilled water. Samples for sorption tests were cut using an angle grinder with a concrete blade into dimensions of 75 × 50 mm. The thickness of all samples used in the test was 13 ± 1.2 mm based on the set-up configuration of the steel mould.

3.4 Statistical analysis

The experiments were designed and analysed based on a central composite design (CCD) using the STATISTICA software v5. Three factors were considered within one block, namely the binder ratio of KH_2PO_4/MgO, the fly ash content as partial replacement of the binder and the wood content as ratio of wood to the total inorganic content. ANOVA was used to determine the significant variables that affected board properties. The response surface method (RSM) was used to establish a statistical relationship between experimental variables and responses, from which the optimal experimental conditions could be predicted for achieving optimum performance according to Bloor and England (1991). Table 1 shows the factors and the corresponding levels for the response surface design.

4 Results and discussion

4.1 Test result

From the design, a total of 16 experimental runs were conducted at random. The summary of the test result is presented in Table 2. Analysis of variance (ANOVA) of the main effects and their interaction was considered for each wood species and the variables that were significant for the board properties are presented in Table 3. Fitted response surfaces were plotted for variables where the interactions were significant ($p < 0.05$) (Figs. 1, 2, 3, 4, 5, 6, 7, 8). The ANOVA analysis showed that there is no significant effect of the factors on the mechanical properties of the boards

Table 2 Board properties

Wood species	MOR (MPa)	MOE (MPa)	Density (g/cm^3)	WA (%)	TS (%)	VS (%)
A. mearnsii	0.73–4.51	11.67–64.51	0.71–0.93	8.99–17.39	0.00–1.23	0.40–5.52
A. longifolia	0.73–1.94	9.57–29.61	0.63–0.91	9.49–26.66	0.09–1.88	0.09–8.68
A. saligna	0.64–3.52	14.05–41.99	0.76–0.95	10.49–17.35	0.02–1.29	0.15–6.49
A. cyclops	0.52–1.71	12.65–31.48	0.77–0.95	9.23–17.30	0.02–1.21	0.35–5.12

Table 3 Effect of the production factors on board properties

Wood species	*p* values		
	Binder ratio	Fly ash content	Wood content
A. mearnsii	WA (0.0485)	WA (0.0091)	WA (0.0141)
A. longifolia	WA (0.0244)	WA (0.0387)	WA (0.0156)
		Density (0.0218)	Density (0.0214)
A. saligna			Density (0.0340)
			VS (0.0386)
A. cyclops			

Values (in parenthesis) are significant for the board property $p < 0.05$

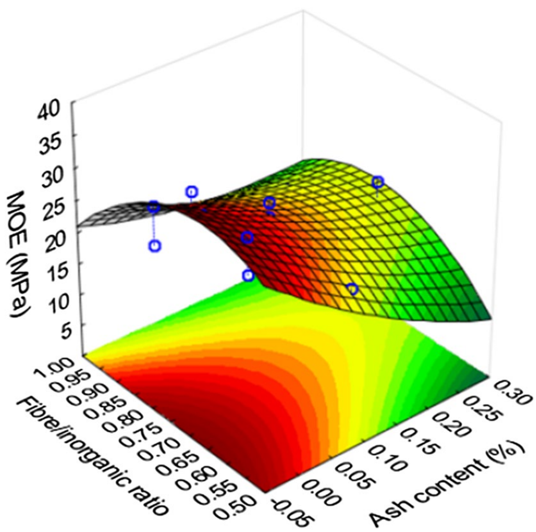

Fig. 1 Fitted surface of MOE for *A. cyclops*

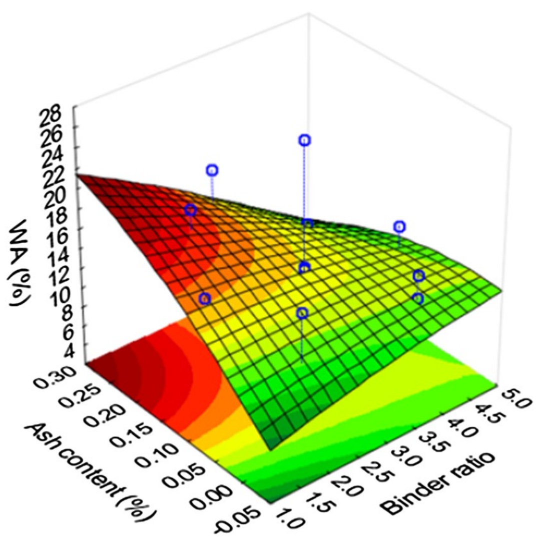

Fig. 2 Fitted surface of WA for *A. longifolia*

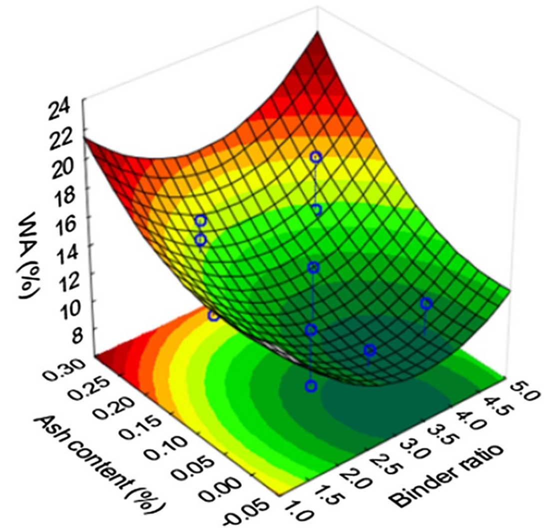

Fig. 3 Fitted surface of WA for *A. mearnsii*

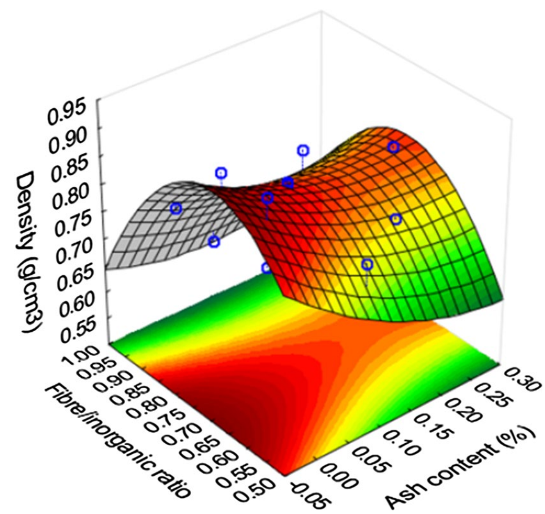

Fig. 4 Fitted surface of density for *A. longifolia*

indicating that none of the variables considered significantly influenced the board strength properties within the experimental design. However, the effect of the independent variables was significant on some physical properties of the boards.

4.2 Effect of the independent variables on board properties

4.2.1 Effect of binder ratio on the board properties

The interaction between fibre/inorganic ratio and fly ash content on the MOE of *A. cyclops* is presented in Fig. 1. It could be observed that at a binder ratio of 2:1, no fly ash

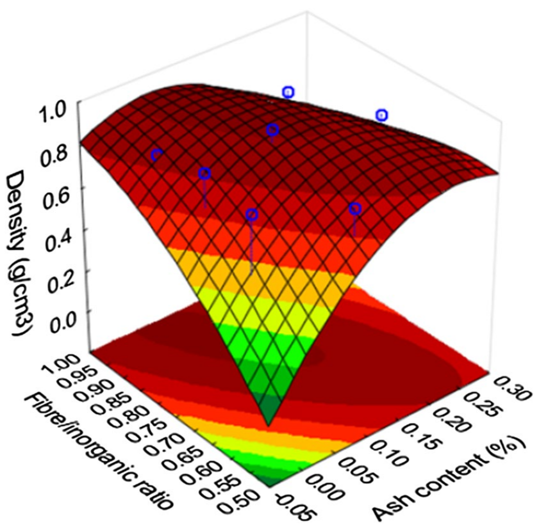

Fig. 5 Fitted surface of density for *A. saligna*

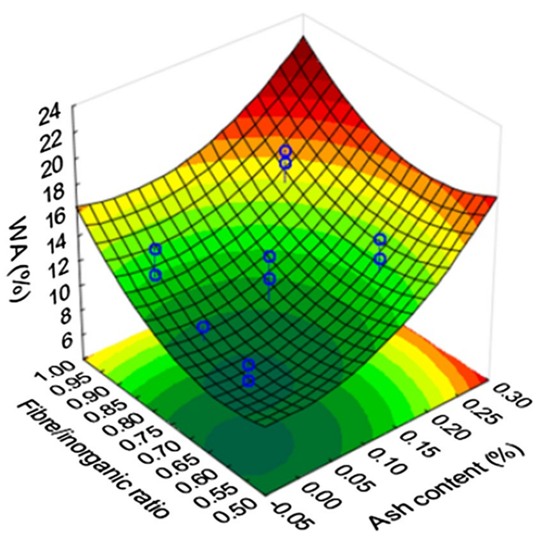

Fig. 6 Fitted surface of WA for *A. mearnsii*

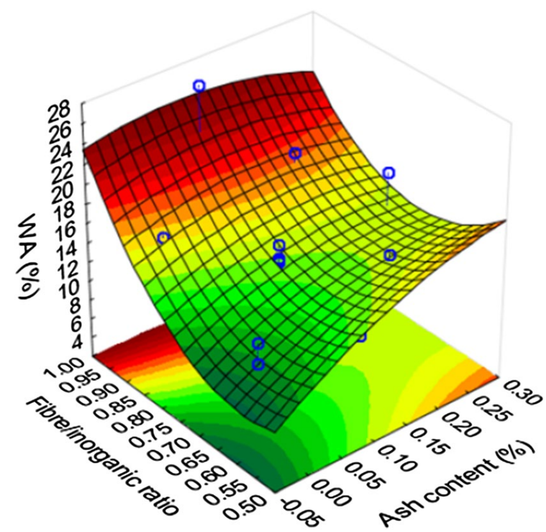

Fig. 7 Fitted surface of WA for *A. longifolia*

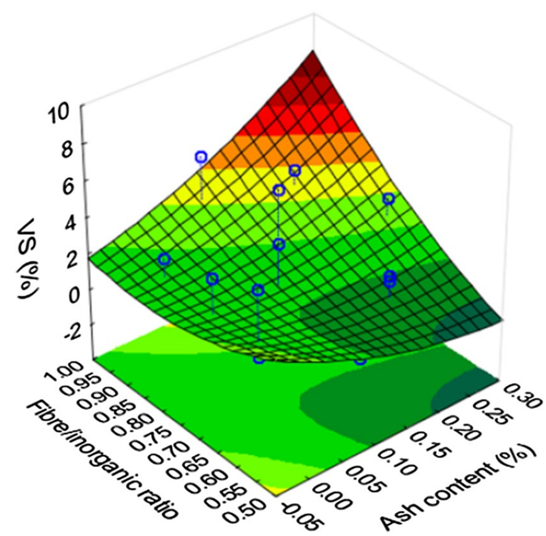

Fig. 8 Fitted surface of VS for *A. saligna*

content and a wood/inorganic ratio of 0.63:1, the highest MOE value was recorded for *A. cyclops*, i.e. 31.48 MPa. At higher fly ash loadings to about 20%, the MOE decreased. This can be explained by the fact that the binder was reduced, and the board did not achieve sufficient stiffness with increasing ash content. However, the strength properties increased with increasing fibre content. High fibre content is known to increase the MOE of fibre reinforced composites (Mohr et al. 2004) as a result of the transmission of the applied stress to the fibres (Cantwell and Morton 1991). Figures 2 and 3 show the effect of the interaction between binder ratio and fly ash content on the board properties. The effect of the binder on the WA of the boards was significant for *A. mearnsii* and *A. longifolia* (Table 3). From the WA fitted surface graphs, it was observed that at low levels of ash content and a corresponding increase in binder content, WA will be lower for the studied species. High binder content increases bonding in wood composites and encapsulates the hygroscopic wood fibres, thereby reducing water absorption.

4.2.2 *Effect of fly ash content on the board properties*

Fly ash plays a role in phosphate bonded composite products by improving its workability and generating more binder (Laufenberg and Aro 2004; Wagh 2013). However, the findings in this study revealed that the

Table 4 Summary of optimized factors for predicting board properties of *A. mearnsii*

Factors	Opt. value to MOR	Opt. value to MOE	Opt. value to density	Opt. value to WA	Opt. value to TS	Opt. value to VS
KH_2PO_4/MgO	1.66	1.66	2.66	3.34	4.68	4.68
Fly ash	0.054	0.027	0.081	0.027	0.27	0.27
Wood/inorganic	0.96	0.96	0.75	0.71	0.67	0.71
Desirability	4.70 MPa	65.23 MPa	0.90 g/cc	8.95%	−0.25%	0.33%

partial replacement of phosphate binder with fly ash, without increasing the wood content, decreased board strength properties, and decreased WA and TS/VS. As binder ratio increases with fly ash content, strength properties increased. A high binder ratio with more fly ash produces more $MgKPO_4.6H_2O$ mineral during hydration resulting in better bonding between fibres (Donahue and Aro 2010). The effect of the fly ash content was significant for both density and WA of *A. longifolia* and WA of *A. mearnsii* (Table 3). Figures 4 and 5 show the interaction between fibre/inorganic ratio and fly ash content at a binder ratio of 3:1 for *A. longifolia* and *A. saligna*. It could be observed that density increases as fibre content and fly ash increase for *A. saligna*. However, with increasing fibre content, fly ash did not contribute to the density of *A. longifolia*. At high loadings of fly ash, the density of *A. longifolia* decreased which had a negative effect on the strength properties.

4.2.3 Effect of wood fibre content on the board properties

Fibres play a significant role in increasing the specific gravity of composites and impart additional energy absorbing capacity to the product (Mohr et al. 2004). In this study, wood content was found to have a significant effect on the density of *A. longifolia* and on the density and VS of *A. saligna* (Table 3). The wood content also had a significant effect on the WA of the boards. Generally, moisture absorption increased with increase in wood content. This is a result of the hygroscopic nature of lignocellulosic fibres. Figures 6, 7 and 8 show that the WA and VS of the boards decreased as the fibre and fly ash content decrease. By increasing binder ratio at low fibre content, the WA of the boards decreases. On the other hand, WA increases as the fibre content increases. Increased binder ratio with corresponding low ash content increases the bonding between fibres, and since the hygroscopic fibres are low in the board, WA is reduced (Amiandamhen et al. 2016).

4.3 Optimization of the independent variables for prediction of board properties

The optimum conditions for predicting the properties in the manufacturing of composite products from wood and agricultural residues were determined from the desirability profiler available in STATISTICA software (v5). As explained by Maran and Manikandan (2012), the desirability function searches for factor combination levels that jointly optimize a set of responses by satisfying each response requirements in the design. The scale of the desirability function ranges between 0 (completely non-desirable) and 1 (fully desired response) (Gonzalez et al. 2007). Individual desirability is obtained by specifying the goals for each response. A weight factor, which defines the shape of the desirability function for each response is assigned, and is usually between 0.1 and 10. A weight factor of 1 was selected for the purpose of this study.

Using numerical optimization, profiles of predicted values and desirability were established to estimate each response as influenced by the independent variables. The optimum process conditions of binder ratio, fly ash and wood content for achieving the desired board properties are presented in Tables 4, 5, 6 and 7. With the optimum values provided, it was observed that the maximum predicted values of MOR of *A. mearnsii, A. longifolia, A. saligna* and *A. cyclops* are 4.7, 1.74, 3.72 and 1.72 MPa respectively compared to the observed values of 4.51, 1.94, 3.52 and 1.71 MPa respectively. Based on the regression model, the quadratic equation for each response variable can be written as follows;

$$y = \mu + ax + bx + cx + a^2x + b^2x + c^2x + abx + acx + bcx$$

The analysis shows a high precision of the model. The high degree of fitting between predicted and observed results reflects the accuracy and applicability of the model in the optimization process (Zhao et al. 2008).

5 Conclusion

This study has demonstrated the feasibility of manufacturing board products from alien invasive tree species found locally in South Africa. The manufacturing of board products could be incorporated into the management practices aimed at controlling the spread of such species. All physical properties evaluated—including density, WA, TS and VS—met the minimum requirements for low density particleboards (EN-634: 1995). The optimum composite

Table 5 Summary of optimized factors for predicting board properties of *A. longifolia*

Factors	Opt. value to MOR	Opt. value to MOE	Opt. value to density	Opt. value to WA	Opt. value to TS	Opt. value to VS
KH_2PO_4/MgO	2.66	1.32	1.66	4.68	4.68	4.68
Fly ash	0.00	0.00	0.00	0.27	0.27	0.27
Wood/inorganic	0.71	0.62	0.75	0.88	0.96	0.96
Desirability	1.74 MPa	29.71 MPa	0.91 g/cc	8.91%	−0.26%	−1.01%

Table 6 Summary of optimized factors for predicting board properties of *A. saligna*

Factors	Opt. value to MOR	Opt. value to MOE	Opt. value to density	Opt. value to WA	Opt. value to TS	Opt. value to VS
KH_2PO_4/MgO	1.32	1.32	1.66	4.68	3.67	3.67
Fly ash	0.00	0.00	0.27	0.027	0.16	0.22
Wood/inorganic	0.54	0.88	0.96	0.58	0.54	0.62
Desirability	3.72 MPa	38.39 MPa	0.96 g/cc	10.38%	0.056%	0.14%

Table 7 Summary of optimized factors for predicting board properties of *A. cyclops*

Factors	Opt. value to MOR	Opt. value to MOE	Opt. value to density	Opt. value to WA	Opt. value to TS	Opt. value to VS
KH_2PO_4/MgO	3.00	2.66	1.32	4.68	4.68	4.68
Fly ash	0.081	0.00	0.054	0.27	0.00	0.27
Wood/inorganic	0.88	0.75	0.96	0.67	0.92	0.96
Desirability	1.72 MPa	31.49 MPa	0.96 g/cc	8.58%	0.0082%	0.32%

manufacturing process for making durable products within the scope of the studied species was found to contain a ratio of $KH_2PO_4/MgO = 1.66$, 2.7% fly ash content and a wood/inorganic ratio of 0.96. To the authors' best knowledge, this is the first time that this binder system has been optimised for such particleboards.

The binder is robust enough to accommodate the variability inherent in these wood species and is not affected by the chemical composition of the species. However, while fly ash can be incorporated to reduce binder cost and the overall cost of the production process, at high quantities, it proved to have a negative effect on strength properties. Although, the variables considered, i.e. binder ratio, fly ash and wood content have significant effect on the physical properties of the board, the effect on the mechanical properties was not significant within the experimental design.

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