Arch. Metall. Mater. **70** (2025), 2, 1193-1198

DOI: https://doi.org/10.24425/amm.2025.154467

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THE EFFECT OF WOOD ADDITION ON THE PROPERTIES OF GEOPOLYMERS: A SHORT REVIEW

One of the latest approaches to substituting the natural aggregates or fibers in the geopolymers is the use of wood waste. The wood flour, chips, or fibers coming from end-of-life furniture or construction and demolition waste can be incorporated into the composition of geopolymers to achieve lighter products and, most importantly, to reduce the use of virgin raw materials. However, when combining inorganic and organic materials into a product that should withstand thousands or hundreds of years, the exhaustive evaluation of the behavior of the obtained composites is very challenging. The current literature mainly approaches the influence of the wood type and amount on the main properties of the geopolymers, but a deep evaluation of the long-term behavior of these wood-aluminosilicate mixtures is still necessary. The current study presents a brief overview of the research conducted on the effect of wood addition on the compressive strength, flexural strength, physical properties, microstructure, and durability of geopolymers. Accordingly, it was concluded that low amounts of wood particles will increase the compressive strength of geopolymer composites. However, the wood presence may result in a slight decrease in durability due to water absorption and the higher porosity of the resulting composite compared to the geopolymer without wood content. Moreover, the current challenges, opportunities, and limitations were identified.

Keywords: Timber waste; geopolymers; ecofriendly materials; circular economy; green concrete

1. Introduction

The current need for construction materials has led to an increased demand for virgin raw materials [1]. To support this increased consumption, it is strongly needed to identify suitable substitutes for the main components of the materials used in construction. Therefore, nowadays, researchers focus on finding solutions to incorporate the high wastes available in high volumes worldwide into the composition of building materials. One of the main directions developed in the last century is the use of alkali-activated materials, or geopolymers, instead of Ordinary Portland Cement (OPC) based materials [2]. However, the need for developing materials with tailored properties cannot be met without properly designing the composition of these eco-friendly materials [3-5]. Usually, this adjustment is strongly related to the composition of the components used for the manufacturing of the geopolymers [6,7]. Therefore, the flexural strength of a brittle matrix can be improved by incorporating different types of fibers, natural or synthetic [8-10]. Also, to decrease the water absorption and improve the compressive strength, different types of particles have been introduced into the mixture [11]. To further reduce the weight of the final product, some researchers have also used wood particles [12-14].

The lignocellulosic wastes consisting of lignin, cellulose, hemicellulose, and extractives have been used as raw materials for many types of geopolymers (metakaolin or fly ash-based) [15]. However, the literature reports contradictory results regarding the influence of sawdust or wood chips as fillers in geopolymer composition.

This study aims to present a brief overview of the potential use of wood waste in the composition of geopolymers and, most importantly, the optimum amount and type of wood that can be incorporated to develop tailored properties.

2. Compressive strength

Asante et al. [16] evaluated the influence of pine or eucalypt particles, untreated or treated in hot water, on the composition of fly ash-based geopolymers. According to their study, the treatment applied to the wood particles showed almost no influence on the compressive strength. However, the type of wood can

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have a significant effect on the mechanical properties, since the maximum compressive strength they obtained for pine particles was around 1.50 MPa, while the geopolymer with eucalyptus particles showed up to 2.59 MPa.

Wang et al. [17] evaluated the influence of introducing wood waste between 20 and 40 vol.% in the matrix of geopolymers on their compressive strength. Finally, they concluded that even if the compressive strength increases over time, the increase in the wood addition will result in a significant decrease in the mechanical properties. This behavior was mainly due to the intrinsic absorption of wood, which will lead to the incorporation of activators in the first stages of hydration. Moreover, over time, the activator will be released during curing, resulting in the formation of large pores and most importantly the cracks in the interfacial transition zone between the artificial aggregates and the matrix.

Weng et al. [18] observed that an addition of 10% wood flour to fly ash-based geopolymers will exhibit the optimum compressive strength compared with other amounts between 5 and 30%. Moreover, they observed that when the proper content is achieved, the water absorbed in the wood could positively influence the hydration reaction, while at too low water content the hydration is incomplete, or a foaming effect will be obtained at too much water.

Wood waste has also been involved in the composition of geopolymers as fibers (wool) to develop ecofriendly boards [19]. After assessing the influence of Na_2O concentration and the GGBFS addition, the same authors concluded that the Na_2O concentration of 12% and the ground granulated blast furnace slag (GGBFS) addition of 15% will exhibit the highest compressive strength. Despite the fact that a concentration of 10 M is usually reported in the literature as the main concentration for the alkali-activated geopolymers, it seems that in those with wood addition, the optimum concentration is 12 M, which could be related to the reaction between the hydroxyl groups present on the wood surface and the excess hydroxide from the activator. Another study [20] assessed the use of 2 wt.% wood fibers in geopolymers with GGBFS, silica fume (SF) and FA mixed with construction demolition waste materials (CDW) and obtained a compressive strength of 33.50 MPa. In acid activated geopolymers, the addition of wood fibers seems to have a negative effect on compressive strength despite the percentage. Lin et al. [21] observed that a 5% addition of wood fibers in metakaolin based geopolymers will result in a 20.9% decrease in compressive strength.

A mixture between wood waste and cenospheres or rubber was designed and tested by Gigar et al. [14]. At 28 days of curing, they obtained up to 15 MPa for the sample with a rubber-to-wood ratio of 25%, while using an addition of 25% waste aggregates in the geopolymer matrix. However, a slight increase from 15 MPa to 17 MPa could be obtained by replacing the fly ash with cenospheres. Also, when mixing the fly ash with GGBFS, the same group of researchers [22] obtained up to 28 MPa. With the same type of matrix, i.e., fly ash mixed with GGBFS, Mehdi et al. [23] obtained more than 45 MPa by using wood sawdust instead of wood chips.

As reported by [24], the type of wood will also have a slight effect on the compressive strength of geopolymers. After the evaluation of E. gradis, E. camal, B. wattle, P. jack, Spurce and Pine addition, they observed that the E. gradis wood will result in an increase in the compressive strength, while all the other five types of wood will contribute to the decrease of this mechanical property. Moreover, when the wood waste was treated with NaOH solution, an up to 21% increase in compressive strength could be obtained.

An overview of the amounts and types of wood used in the mixtures of geopolymers is presented in TABLE 1. As can be seen, for the fly ash based geopolymers, the mixture with the highest compressive strength is the one with 10 wt.% wood flour, while when the wood is used in the form of chips, a maximum compressive strength of 15 MPa can be obtained for an addition of 25 wt.%. Wood flour also seems to be the most preferred form even when flu ash GGBS blended geopolymers are tested. In the case of all the evaluated mixtures, the geopolymers that used metakaolin as an aluminosilicate source exhibited the highest compressive strength.

TABLE 1

The compressive strength of geopolymers with different types and amounts of wood waste

Matrix type	**Wood-type**	**Amount**	**Compressive strength, MPa**	**Reference**
Fly ash	Wood flour	10 wt.%	69.1	Weng et al. [18]
Fly ash	Pine-particles	20 wt.%	1.5	Asante et al. [16]
Fly ash	Eucalypt--particles	20 wt.%	2.59	
Fly ash	E. gradis	20 wt.%	13.77	Asante et al. [24]
	E. camal,	20 wt.%	13.2	
	B. wattle	20 wt.%	13.5	
	P. jack	20 wt.%	13.1	
	Spurce	20 wt.%	11.87	
	Pine	20 wt.%	11.11	
Fly ash	Wood chips	25 wt.%	15	Gigar et al. [14]
Metakaolin	Wood fibers	5 wt.%	82.4	Lin et al. [21]
Metakaolin	Wood fibers	10 wt.%	78.5	
Fly ash & GGBFS	Wood chips	10 wt.%	26	Gigar et al. [22]
Fly ash & GGBFS	Wood wool	30 wt.%	1.4 (σ10)	Koh et al. [19]
Sulfoaluminate cement	Fruit wood	30 vol.%	25	Wang et al. [17]
Sulfoaluminate cement	Fir wood	30 vol.%	21	
Sulfoaluminate cement	Pine wood	30 vol.%	23	
Sulfoaluminate cement	Pine-particles	20 vol.%	34.8	
OPC	Pine-particles	20 vol.%	16	
Mineral powder	Pine-particles	20 vol.%	30	

3. Flexural strength

In the case of flexural strength, the most significant effect is given by the shape of the wood waste. Therefore, the highest flexural strength is achieved with the incorporation of wood as fibers. Compared to compressive strength, in the case of flexural strength, a slight improvement was observed when increasing the amount of wood [21]. However, this behavior is only related to the addition of wood fibers, since when flour or chips are used, the flexural strength also decreased when the amount of wood was increased in the composition [17]. By incorporating 15% wood fibers into the composition of geopolymers, the flexural strength was 2.26 higher compared to that of the control sample [21]. The positive influence on the flexural strength will exhibit a maximum at 25 wt.% of wood, and then supplementary amounts will result in a decrease in both mechanical properties, i.e., compressive and flexural strength [22].

4. Physical properties

Depending on the type of wood, geopolymer wood composites may exhibit a slight difference in porosity (Fig. 1). As reported in [16], the porosity of the materials with pine wood was 47.21%, while those with eucalyptus wood showed 47.13%. However, significant differences were observed in bulk density, i.e., 0.88 g/cm^3 for those with pine wood and 1.03 g/cm^3 for those with eucalypt wood, and water absorption, where the mixture with Eucalypt particles showed almost 46%, compared to 53.53% of that with pine particles. Along with the type of wood, the bulk density of this composite is also influenced by the Na_2O concentration from the activator. As observed by Koh et al. [19] the increase in Na_2O concentration from 6% to 12% will increase the bulk density from 340 kg/m^3 to 440 kg/m^3. The same parameter also significantly influenced the thermal conductivity resulting in an increase of almost 15%. However, by replacing the natural aggregates with fine and coarse sawdust a significant decrease in the thermal conductivity of geopolymers can be obtained. Mehdi et al. [23] reported a 5 times higher heat transfer time when substituting all the natural aggregates with wood particles. Wang et al. [17] also reported a direct relation between the amount of wood aggregates and the thermal conductivity of the geopolymer composites. Moreover, they reported that higher amounts of wood will result in low thermal conductivity, but also poor mechanical performance.

5. Microstructure

The microstructural analysis of the geopolymers with wood particles reveals the challenges in obtaining a composite without structural defects. As can be seen from Fig. 2 between the geopolymer matrix and the wood chips usually cracks will occur. These cracks will act as defects and will consequently lead to a decrease in mechanical properties. This behavior could explain the poor compressive strength of the composites with high amounts of wood. Also, the cracks in the interface zone could also be related to the high differences between the toughness of the matrix and that of the wood since, under external forces, the compact geopolymer matrix will cause elastic deformation of the wood and subsequently delamination after the stress is removed [25]. Moreover, the crack formation could also be related to the shrinkage of the wood during curing or drying [26]. The microstructural analysis at high magnification also reveals that the wood particles will absorb or embed the matrix into the cells (Fig. 2(a)), while at low magnification only the presence of cracks in the interfacial transition zone could be observed (Fig. 2(b)). As can also be seen from Fig. 3, the absorption of the geopolymer matrix into the wood particles will lead to an increased density and stronger bond between the components of

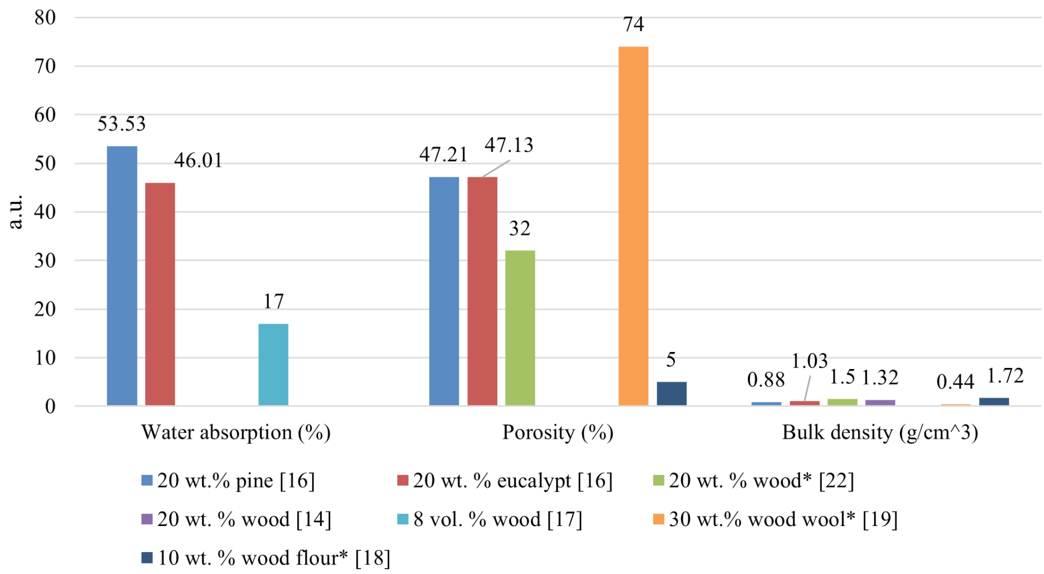

Fig. 1. The influence of wood addition on the physical properties of geopolymers (*the values for the references marked with * are approximated from the charts published in the cited papers*)

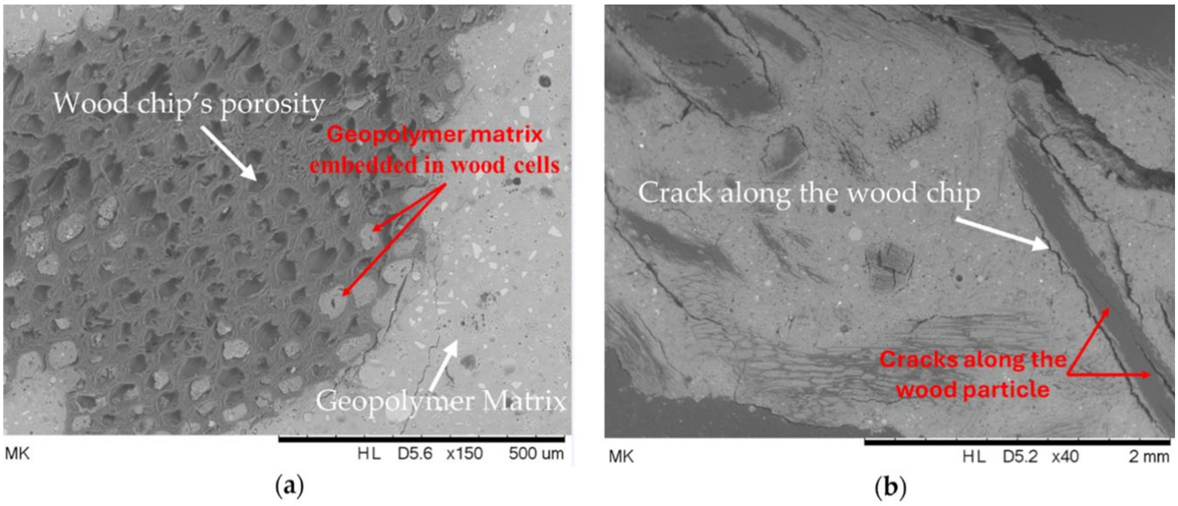

Fig. 2. Microstructural analysis of geopolymers containing wood chips: (a) wood particles embending geopolymer matrix; (b) interfacial transition zone (adapted from [14]

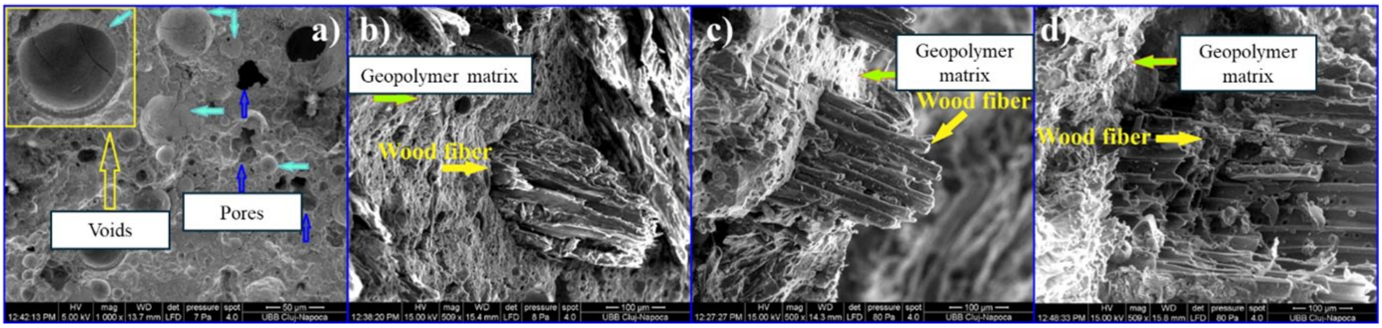

Fig. 3. The morphology of the fly ash geopolymers with different amounts of wood: (a) geopolymer matrix; (b) with 10 wt.% wood; (c) with 25 wt.% wood; (d) with 35 wt.% wood (adapted from [29])

these composites [22]. The high adhesion between the bentonite-based geopolymer and wood surface was also demonstrated by Gonultas et al. [27] which studied the potential substitution of petroleum-based urea formaldehyde adhesives to geopolymer paste. Ye et al. [28] performed pull out tests to evaluate the interfacial bonding properties between wood surfaces and geopolymers. Moreover, they observed that between beech and spruce, the beech wood will exhibit stronger mechanical interlocking. Also, for both types of wood, the interfacial bonding could be improved by sanding the wood surface and by embedding it into the geopolymer at an optimum depth of 25 mm.

6. Durability

To assess the durability of the geopolymers with wood addition, Asante et al. [16] performed an aging test consisting of 200 cycles of soaking and drying. Based on their evaluation, the compressive strength of these composites will decrease over time, especially in the case of those with untreated wood waste. Moreover, the thermal or alkali treatment of the wood surface will also improve the interfacial bonding properties [28].

The life cycle assessment of geopolymer bio-composites showed encouraging results compared to the environmental impact produced by other products that incorporate wood waste. According to Bajare et al. [30], these types of composites are producing around 68.15 kg CO_2 eq. per square meter of wall compared to bio-composites based on starch which exhibited 82.89 kg CO_2 eq. per square meter of wall.

7. Conclusions

The compressive strength of geopolymers could be improved by incorporating low amounts of wood particles. Also, to increase the flexural strength of these composites, up to 25 wt.% of wood wastes in the shape of fibers can be incorporated.

The wood addition will mainly show a positive influence on the thermal insulation capacity of these composites. However, the durability of the geopolymers will be decreased, due to a significant increase in porosity and water absorption.

8. Further directions and limitations

Currently, the literature lacks a deep understanding of the wood behavior in the alkaline environment specific to the geopolymer mixtures. Moreover, it seems that a proper method of treating the wood to avoid cracks and delamination between the wood and the geopolymer matrix wasn't identified.

Due to the intrinsic porosity of the geopolymers as well as the wood particles, the use of these composites seems to be limited to indoor applications because during water absorption, the volume of the wood will increase, then decrease during drying, which will result in fast deterioration of the geopolymer structure and consequently a rapid decrease in mechanical properties. Moreover, in some regions, freeze-thaw cycles specific to winter will affect the structure of these composites even more.

Further research should be conducted on identifying a proper method for reducing the water absorption of the wood used in these composites. Also, durability studies should be conducted on evaluating the freeze-thaw resistance and finding proper methods of mitigating these limitations.

Acknowledgement

This work was supported by a National Research Grants of the TUIASI, project number GNaC 2023_271/2024, Prefabricate inovative pe bază de compozite geopolimerice cu adaos de deșeuri lemnoase (Pre-Geo).

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