

Mechanical Properties and Volatile Pollutants Absorbing Capacity of Mortar Composites with Addition of Coconut Shell Activated Carbon and Gamal Wood Chips Aggregates

Baiq Mirawati^{1*}, Muhammad Sadir¹, Albert Hendriko², I Gde Adi Suryawan Wangiyana¹,
Ismail Budiman³, Dede Hermawan⁴, Gustan Pari³, and Ariadne Lakshmidewi Juwono²

¹Department of Forestry, Faculty of Engineering and Applied Sciences, Universitas Pendidikan Mandalika, Mataram 83125, Indonesia

²Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Indonesia, Depok 16424, Indonesia

³Research Center for Biomass and Bioproducts, Badan Riset dan Inovasi Nasional, Cibinong 16911, Indonesia

⁴Department of Forest Products, Faculty of Forestry and Environment, IPB University, Bogor 16680, Indonesia

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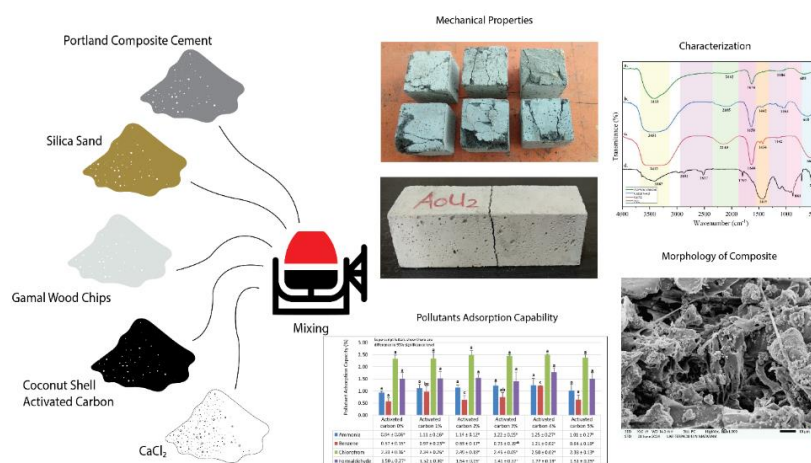
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* Corresponding author:

E-mail:

baiqmirawati@undikma.ac.id

GRAPHICAL ABSTRACT



ABSTRACT

The use of biomass has the potential to improve the mechanical characteristics of cement-based composites. Activated carbon is considered competitive in absorbing hazardous pollutants in the air, is able to reduce cracking and increase the mechanical strength of cement-based composites. The addition of gamal wood chips also has the potential to increase flexibility in mortar composites. The purpose of this study was to analyze the characteristics of the mechanical properties and pollutant absorption capacity of mortar composites with the addition of activated carbon and gamal wood chips. In this study, activated carbon is used as a fine aggregate (filler) with an addition of 1-5% to the weight of cement. Gamal wood chips are used as much as 1.5% of the total weight. Composite brick testing includes density, compressive strength, modulus of elasticity (MOE), modulus of rupture (MOR), adsorption capacity for ammonia, benzene, chloroform, and formaldehyde and thermal analysis of Field Emission Electron Microscopes (FE-SEM) and Fourier-transform infrared spectroscopy (FTIR). The density of composite mortar with the addition of activated carbon and gamal wood chips ranges from 1950.36±19.54-2137.24±45.09 kg/m³, compressive strength 8.48±0.76-9.71±1.68 MPa, MOE 421.74±69.59-645.58±57.51 MPa, MOR 2.14±0.27-2.75±0.20 MPa. The composite mortar exhibited a total pollutant absorption rate of less than 3% for all tested parameters. The addition of activated carbon up to 4% can increase the mechanical strength and pollutant absorption capacity and can produce more CaCO₃ in composite bricks. Morphological observations as analyzed by FE-SEM, were found to correlate with FTIR analysis, namely the formation of CaCO₃. The following method produces an environmentally friendly mortar composite that performs exceptionally well and has a lot of potential for use in sustainable building.

HIGHLIGHTS

- Activated carbon and gamal wood chips enhanced mortar composite performance.
- A 4 wt% activated carbon addition produced the optimum mechanical properties.
- Composite mortar showed measurable adsorption of ammonia, benzene, chloroform, and formaldehyde.
- FE-SEM and FTIR analyses confirmed enhanced CaCO₃ formation in the composites.
- The developed mortar offers a sustainable and environmentally friendly building material.

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1. INTRODUCTION

Along with the development of a civilization, especially after the industrial revolution, human intervention often causes air pollution to become an unavoidable problem, where the consequences of this air contamination can specifically affect health and mortality rates in various nations, especially those that are left behind and still developing (Meda et al., 2022). One of the major emissions that is a pollutant is ammonia (NH₃) emissions, which amount to ~80% comes from the agricultural sector, where ammonia is actually a precursor to fine particulate matter (PM 2.5) which is more dominant than nitrogen oxide (NO_x) and sulfur dioxide (SO₂); and contributes to respiratory health problems (Wyer et al., 2022). Chloroform (CHCl₃) is also one of the largest contributors to atmospheric chlorine emissions that can have an impact on ozone damage, where chloroform often appears due to various organic matter found in the soil naturally or deposited due to human intervention such as its use in various refrigerants (Enyoh et al., 2020; Zhang et al., 2021).

In a study conducted by Van Tran et al., (2020) it was explained that indoor air pollution also has a significant impact on human health (mortality of ~3.8 million people per year), where humans spend 90% of their time indoors. Formaldehyde (HCHO) compounds are volatile compounds that produce emissions from indoor furniture produced from the use of resin, paint, and varnish in the manufacturing process, where this compound contributes to soft tissue irritation in the respiratory tract, nose, eyes, and has the potential to be carcinogenic (Mannan and Al-Ghamdi 2021; Salthammer, 2019). Benzene is a volatile compound that is unknowingly present as an indoor pollutant caused by heating and combustion processes such as smoking and cooking with fossil fuels, where benzene has the potential to be carcinogenic (Sekar et al., 2019; Zhang et al., 2020).

Activated carbon is a widely used adsorbent that can be produced from biomass waste such as coconut shells. Coconut shells are widely utilized as biomass waste owing to their hardness, high carbon density, and renewability. While coconut shells offer a renewable feedstock for activated carbon production, the conventional manufacturing route, which relies on high-temperature pyrolysis under inert conditions, is energy-intensive. This results in a substantial embodied energy within the product and a considerable carbon footprint, posing a significant challenge to the overall life-cycle sustainability of the

material. The use of coconut (*Cocos nucifera*) shells as activated carbon (Figure 1(d)) has succeeded in becoming a highly useful commodity and is easily obtained commercially, in addition to having high availability and competitive prices, this material has stable and environmentally friendly physicochemical characteristics (Wang et al., 2019; Sujiono et al., 2022). The use of activated carbon from biomass as an option for absorbing pollutants has begun to be widely developed to overcome environmental pollution problems, in addition to being more sustainable and easily regenerated, this biomass activated carbon has resistance to high temperatures, resistance to strong acids and bases, and good chemical stability (Gayathiri et al., 2022). Research conducted by Sadir et al. (2022) used activated carbon from kenaf stems (*Hibiscus cannabinus* L.) to absorb hazardous volatile compounds such as ammonia, benzene, chloroform and formaldehyde.

Gliricidia sepium (Figure 1(a)-(b)) is a type of leguminous plant that is widely found in tropical and subtropical areas starting from Southeast Asia, Sub-Saharan Africa, to Central America, which has many uses especially in terms of reforestation, soil preservation, and organic fertilizer (Barberi, 2019; Aulanni'am et al., 2021; Alamu et al., 2023). Coulibaly et al. (2017) explained that *G. sepium* is a plant that has the potential to contribute nutrients to the soil in the form of organic compounds and nitrogen; and its wood waste is widely used as firewood. In Indonesia, *G. sepium* is known as gamal wood, which is widely used for shade plants in various plantations because it has good morphology and grows quickly in non-ideal soil conditions, such as in soil with high calcium content (Khusnul et al., 2020). Barberi (2019) explained that biomass production from coppicing fallow legume species such as *G. sepium*, *Leucaena trichandra*, and *Calliandra calothyrsus*; is 8 times higher than from non-coppicing fallow legume species such as *Sesbania sesban*, *Mucuna pruriens*, and *Tephrosia vogelii*.

As a composite material, concrete has mechanical advantages such as high compressive strength, good heat insulation, sound absorption capacity, fire resistance, and seismic damping (Aslam et al., 2016). Despite its superior performance, concrete composites have weaknesses that affect their performance, such as low tensile strength and ductility, so that concrete is susceptible to cracking because the tensile strength value is lower than the compressive strength value (Hermawan et al., 2022). In the process

of making cement as the main raw material for concrete, it is one of the contributors to carbon emissions in the world ($\sim 7\text{--}8\%$ CO_2), so the development of sustainable concrete is very relevant to answer this problem (Nilimaa, 2023). Onyelowe et al. (2022) explains that

one of the efforts to develop sustainable concrete is to use various renewable materials to reduce or replace concrete materials that have an environmental impact, with the hope of maintaining or improving the mechanical properties of the concrete.



Figure 1. Picture of: a. Gamal wood plant; b. Cross section of gamal wood; c. Gamal wood chips; d. Coconut shell activated carbon

The development of natural materials and other lignocellulosic cement-based materials will be able to bond well into composites if the chemical components of hemicellulose and wood extractives are first removed or reduced; one of which is done by hydrothermal carbonization which is more environmentally friendly and effective in reducing the content of hemicellulose and wood extractives at low temperatures (Majzoobi et al., 2016). Increasing concern for environmental issues, urging more versatile environmentally friendly materials, has led to increasing attention to polymer composites, namely fillers or reinforcing materials derived from renewable and biodegradable sources (Alzard et al., 2022). The use of activated carbon as an additional aggregate to improve the quality of cement composites has gained high traction in this decade, such as in the study of Zheng et al. (2017) explained that there was an improvement in the mechanical properties (compressive and flexural strength) of cement mortar with the addition of powdered activated carbon aggregate up to 2.0%. One of the advantages of using activated carbon as an aggregate is that it can increase the adsorption capacity of volatile organic compounds as in the study of Krou et al. (2015) where the addition of activated carbon to cement paste can increase the adsorption capacity of acetaldehyde and toluene.

Prior research has explored the enhancement of mechanical and functional properties of concrete through various additives. For instance, a composite incorporating 4% NaOH-modified wood powder combined with 3% silane coupling agent demonstrated

improvements in flexural and compressive strength. Specifically, flexural strength increased by 31.6% compared to mortar without wood powder, and by 27.1% compared to mortar containing unmodified wood powder. Meanwhile, compressive strength showed a 28.7% increase relative to the unmodified wood powder composite, although it remained slightly lower than the control mortar without wood powder (35.4 MPa vs. control) (Li et al., 2025). Regarding pollutant adsorption, high-silica fly ash (SDS-FA) modified with sodium dodecyl sulfate achieved a maximum methylene blue adsorption capacity of 84.46 mg/g, while mesoporous silica material (MSM) reached 115.34 mg/g, underscoring the enhanced efficiency achieved through material modification (Guo et al., 2024).

However, existing approaches often focus on improving a single performance aspect either mechanical or functional potentially at the expense of other properties. Consequently, a knowledge gap exists in the development of mortar composite materials that achieve synergy between enhanced mechanical properties particularly tensile and flexural strength and significant pollutant adsorption capacity. Technically, this study does not merely evaluate partial aggregate substitution but aims to create an integrated composite system wherein the two materials complement each other gamal wood chips serve as a lightweight filler, while activated carbon particles function as an adsorbent agent. This combination has the potential to equip the mortar with the ability to adsorb air pollutants, regulate humidity, and enhance bonding within the

cement matrix through the microscopic porous structure of the activated carbon. Based on this explanation, the purpose of this study was to analyze the characteristics of the adsorption capacity of hazardous pollutants of composite mortar with the addition of commercial activated carbon from coconut shells and to analyze the characteristics of the mechanical properties of composite mortar with the addition of activated carbon from coconut shells and gamal wood chips (*G. sepium*).

2. METHODOLOGY

2.1 Materials

The main materials that used in this research are the form of portland composite cement (PCC) (Bosowa); silica sand taken from local miners in East Lombok, Indonesia; gamal wood (*G. sepium*) taken from local plantations in Sedau, Central Lombok, Indonesia; and commercial coconut shell activated carbon (AF Carb). For additives, calcium chloride (CaCl_2) was used with the aim of creating a more

stable mixture and controlling the hydration rate so that it can potentially become an accelerator that accelerates the formation of silica sand strength (Salain, 2019; Almajed et al., 2023). The solutions used as a reflection of pollutants were 25% ammonia solution, benzene solution, chloroform solution, and 37% formaldehyde solution.

2.2 Research methods

The research process is divided into three stages. In the first stage, gamal wood chips were made and the raw materials were characterized before the composite mortar was made. In the second stage, cubes and blocks of composite mortar were made, followed by various mechanical tests such as compression tests, density measurements, modulus of elasticity tests, modulus of rupture tests, and pollutant absorption analysis. In the third stage, the selected mortar composition was characterized using FTIR and microstructural analysis using an electron microscope. Figure 2 shows a more comprehensive and thorough research flow.

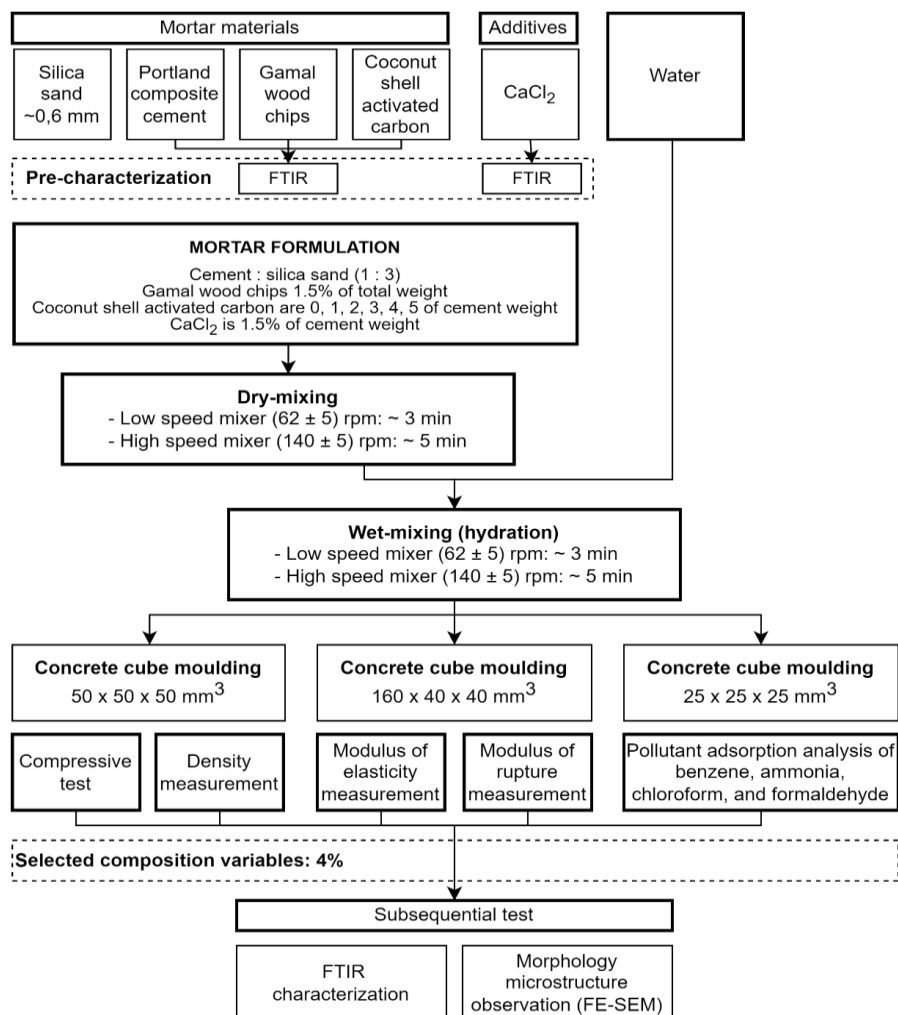


Figure 2. Research flowchart

2.2.1 Manufacturing process of gamal wood chips

Gamal wood is dried in the sun to reduce its water content to <10% which is measured by sampling using a moisture meter. After being separated from its skin, the gamal wood is cut into 1-2 cm sizes. Furthermore, the gamal wood chips are boiled using boiling water for 2 h. This aims to clean the dirt that is still attached, then the gamal wood chips are dried again until they reach a water content of <10%. Gamal wood chips can be seen in [Figure 1\(c\)](#).

2.2.2 Preliminary characterization of mortar composition using Fourier-Transform Infrared Spectroscopy (FTIR)

Characterization using FTIR (Perkin Elmer) was used to determine the chemical bonds contained in the mortar raw materials in this study, namely coconut shell activated carbon, gamal wood chips, CaCl_2 , and portland cement. This material characterization was used in the initial stage as confirmation that the material used was in accordance with its characteristics and uses, where 2 mg of each finely ground sample was analyzed with a resolution of 32 cm^{-1} at a wave number of $450\text{-}4,000 \text{ cm}^{-1}$

([Emmanuel et al., 2015](#); [Tighsazzadeh et al., 2019](#); [Jesus et al., 2024](#)). This FTIR characterization was also carried out on selected mortar composition specimens that had the best mechanical properties.

2.2.3 Manufacturing of mortar composite

Composite mortar in the form of mortar is made with a mixture of sand, cement, water, gamal wood chips, additives (CaCl_2), and coconut shell activated carbon. The manufacture of composite mortar is carried out by adopting SNI 8837-1:2019 ([BSN, 2019](#)). The ratio of cement and sand is 1:3, with the percentage of water addition of 50% of the weight of the cement (w/c ratio 0.5). Furthermore, activated carbon is added with a percentage of 1, 2, 3, 4, and 5% of the weight of the cement, and CaCl_2 of 1.5% of the weight of the cement. Gamal wood chips are used as much as 1.5% of the total weight of the mortar formulation mixture. Wood swells when it absorbs water; hence, adding wood chips to the mortar is expected to affect the fresh and hardened properties of the mixture, particularly its workability, density, and dimensional stability under varying moisture conditions. The formulation for making composite mortar can be seen in [Table 1](#).

Table 1. Mortar formulation

Sample code	Materials				Additives	Total weight (kg)	Water (L)
	PCC	Silica sand 0.6	Gamal wood chips	Activated carbon	CaCl_2		
	kg	kg	kg	kg	kg		
Activated carbon 0%	3	9	0.18	-	0.045	12.225	1.5
Activated carbon 1%	3	9	0.18	0.03	0.045	12.255	1.5
Activated carbon 2%	3	9	0.18	0.06	0.045	12.285	1.5
Activated carbon 3%	3	9	0.18	0.09	0.045	12.315	1.5
Activated carbon 4%	3	9	0.18	0.12	0.045	12.345	1.5
Activated carbon 5%	3	9	0.18	0.15	0.045	12.375	1.5

In this experimental investigation, silica sand was selected for its high SiO_2 content to promote pozzolanic reactions and enhance mortar properties, with its technical benefits justifying the higher cost. A fixed 1.5% dosage of Gamal wood chips was employed across all mixtures as a controlled secondary variable, enabling isolated evaluation of activated carbon content (0-5%) as the primary variable; this dosage was chosen based on preliminary studies or literature to minimize adverse effects such as increased porosity or weak interfacial zones. The manufacture of composite mortar mixture begins with

mixing dry ingredients according to the composition used using a mixer (3 min, 60 rpm and 5 min, 140 rpm). Hydration is carried out by adding water mixed with a mixer at the same time and speed as dry mixing. The mixture is poured into a mold with dimensions of $50 \times 50 \times 50 \text{ mm}^3$ and left for 24 h to set, then cured in water for 28 days. The manufacture of mortar cubes in more detail will be explained in point 2.2.4 regarding the compression test by adopting the method from SNI 03-6825-2002 ([BSN, 2002b](#)). The results of the manufacture of mortar cubes can be seen in [Figure 3\(a\)](#).



Figure 3. Test specimen; a. mortar cube; b. sample weight; c. and compressive test; d.

2.2.4 Compressive strength test

Compression testing was carried out based on SNI 03-6825-2002 (BSN, 2002b). In line with the mortar making process, the homogeneous mortar mixture was molded into a steel mold with dimensions of $5 \times 5 \times 5 \text{ cm}^3$. The molding was done in 2 layers to avoid too much air being trapped. Each layer must be compacted 32 times with 4 rotations and must be started no later than 2.5 min after mixing.

The upper surface of the test cube mold was leveled and allowed to set overnight (24 h) and then released from the mold and cured in a tub filled with clean water. The curing time was determined periodically until the 28th day. Samples for the compression test in this study were taken in triplicate at the curing time on the 28th day. The compression test was carried out with a 1000 KN universal testing machine (Controls) and is shown in Figure 3(c)-(d). The results of the compression test can be calculated using Equation 1, where f'_m is the compressive strength (MPa), $P_{\max}$ is the maximum compressive force (N), and A is the test cross-sectional area (cm^2).

$$f'_m = \frac{P_{\max}}{A} \quad (1)$$

2.2.5 Measurement of density

Density measurements were carried out based on SNI 03-6825-2002 (BSN, 2002b) using sample specimens with dimensions similar to the sample specimens used for the compressive strength test, namely $5 \times 5 \times 5 \text{ cm}^3$. The sample specimens tested for density were sample specimens in a condition that had been set and had been air-dried in room conditions (not in wet conditions after soaking). Density measurements can be seen in Figure 3(b) and are

calculated using Equation 2 where ρ is the mortar density (kg/m^3), m is the mass of the sample (kg), and v is the volume of the sample (m^3).

$$\rho = \frac{m}{v} \quad (2)$$

2.2.6 Modulus of elasticity (MOE) and Modulus of rupture test (MOR)

Measurement of modulus of elasticity and modulus of rupture were carried out simultaneously by adopting the method of EN 1015-11-2000 (CEN, 2000), where in the elastic modulus the test specimen can still return to its original shape, while in the modulus of rupture the test specimen is pressed to its breaking point. Figure 4 shows the process of testing the modulus of elasticity and modulus of rupture.

The test specimen was molded in the form of a block with a size of $160 \times 40 \times 40 \text{ mm}^3$. The modulus of elasticity is calculated by Equation 3 where MOE is the modulus of elasticity (MPa), P is the load before the proportion limit (N), ΔY is the bending distance at the load P (mm), L is the height of the support (mm), b is the length of the test specimen (mm), and h is the thickness of the test specimen (mm). The modulus of rupture is calculated by Equation 4 where MOR is the modulus of rupture (MPa), P is the load before the proportion limit (N), L is the height of the support (mm), b is the length of the test specimen (mm), and h is the thickness of the test specimen (mm).

$$\text{MOE} = \frac{\Delta PL^3}{4\Delta Ybh^3} \quad (3)$$

$$\text{MOR} = \frac{3PL}{2bh^2} \quad (4)$$

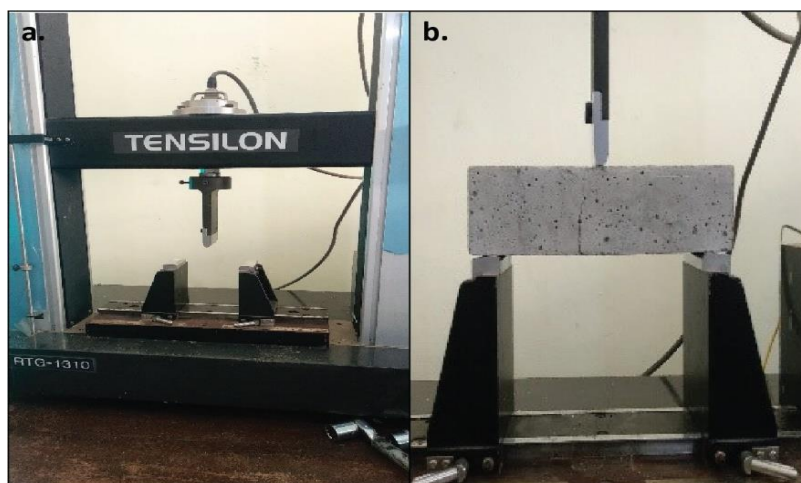


Figure 4. Flexural test specimen: a. instrument for bending test; b. testing procedure

2.2.7 Pollutant adsorption analysis

Pollutant adsorption testing was carried out by adopting the method from SNI 06-3730-1995 (BSN, 1995), where in principle pollutant absorption is seen from the difference in weight of the test specimen. Pollutants are reflected with technical solutions in the form of ammonia, benzene, chloroform, and formaldehyde. The test specimen was printed in a size of $2.5 \times 2.5 \times 2.5 \text{ cm}^3$ and weighed its initial weight and then stored in a desiccator for 24 h with the bottom

(where the silica gel is) replaced with 100 mL of pollutant solution. The volatile nature of this pollutant solution will cause it to be absorbed into the mortar specimen. Pollutant adsorption testing is seen in Figure 5 and calculated using Equation 5, where N is the percentage of pollutant adsorption (%), W_1 is the initial weight of the test specimen (g), and W_2 is the final weight of the test specimen (g).

$$N = \frac{W_2 - W_1}{W_1} \times 100\% \quad (5)$$



Figure 5. Pollutant adsorption test: a. Mortar cube; b. Sample weight; c. Pollutant induction in desiccator

2.2.8 Microstructure analysis on selected composition using field emission - scanning electron microscope (FE-SEM)

Morphological observation of mortar samples was carried out using Field Emission - Scanning Electron Microscope (JEOL) imaging using back-scattered electrons with an intensity of 10 keV Choi et

al. (2005) with a magnification of $300\times$ and $1000\times$. The preparation of test specimens was carried out by adopting the method in Nemati (1997), where the samples were cut with dimensions of $25 \times 25 \text{ mm}^2$ and a thickness of 5 mm which were fixed with a 25mm diameter glass slide.

2.3 Data analysis

Statistical analysis was conducted on the results of compression, density, modulus of elasticity, modulus of rupture, and percentage of pollutant adsorption capacity tests. Statistical tests were conducted using the one-factor completely randomized design (CRD) method and Duncan's test with a significance level of 95%.

3. RESULTS AND DISCUSSION

3.1 FTIR analysis of raw materials

The characterization of materials in this study includes coconut shell activated carbon, gamal wood chips, calcium chloride (CaCl_2), and portland cement using FTIR which is shown in the collection of spectra in Figure 6. The FTIR spectrum of activated carbon in Figure 6(a) shows absorption bands related to hydroxyl groups, carboxyl groups, phenolic hydroxyl groups, and carbonyl groups. The hydroxyl group (O-

H) is shown at a wave number of $3,433\text{ cm}^{-1}$. The wave number of $2,062\text{ cm}^{-1}$ indicates the presence of a $\text{C}\equiv\text{N}$ bond, where bonds with nitrogen elements are common in plant-based materials (Xie et al., 2020; Nedjai et al., 2021). The wave number of $1,636\text{ cm}^{-1}$ indicates the $\text{C}=\text{C}$ group in the aromatic ring as a result of changes in the C-O group, and the activity of the carboxyl-oxygen atom (Ahmad et al., 2015; Lazim et al., 2015). The wave number of $1,086\text{ cm}^{-1}$ is the C-O group, which is a stretch in the lactonic group, alcohol and carboxylic group (Kumar et al., 2013; Deng et al., 2009). The wave number of 688 cm^{-1} indicates the presence of aromatic C-H groups (Koseoglu and Akmil-Basar, 2015). Functional groups like C-O stretches in cellulose/lignin, aromaticity peaks, and oxygenated groups to assess stability, surface chemistry, and activation effects (McCall et al., 2025; Marangon et al., 2025).

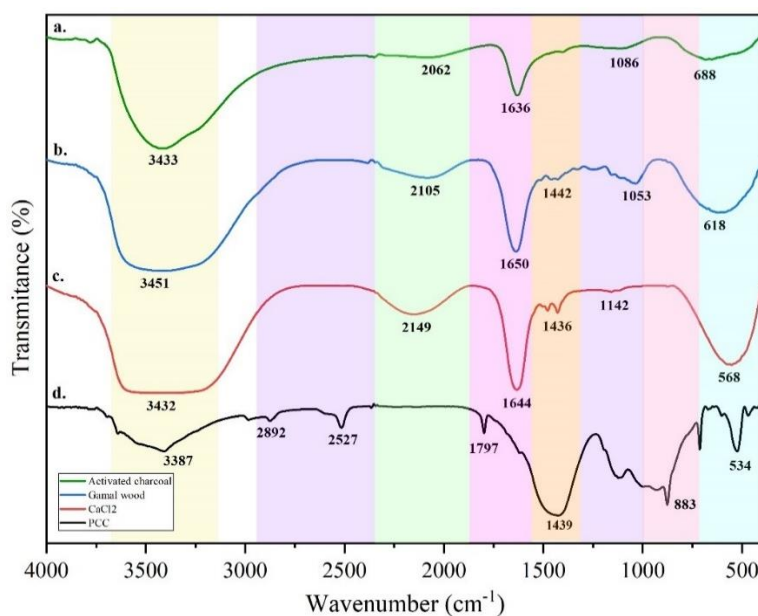


Figure 6. FTIR Spectra: a. activated carbon; b. gamal wood; c. CaCl_2 ; d. PCC

The FTIR spectrum of gamal wood chips in Figure 6(b) shows absorption bands related to alcohol, aldehyde, alkane, amine, aliphatic and aromatic groups. At a wave number of $3,451\text{ cm}^{-1}$ shows the O-H group caused by phenolic and alcohol compounds (Oladunmoye et al., 2018). The O-H group in gamal wood affects the curing process of cement. The wave number of $2,105\text{ cm}^{-1}$ shows C-H stretching, the identified compound is carbonyl. This absorption area is caused by alkanes and alkenes (Valdivielso et al., 2023). The same results were obtained in the study

Oyelere and Oluwadare (2019). Wave number $1,650\text{ cm}^{-1}$ indicates $\text{C}=\text{C}$ stretching, Wave number $1,442\text{ cm}^{-1}$ indicates C-H group, chemical compounds in both absorptions are alkanes. Absorption band $1,053\text{ cm}^{-1}$ indicates C-N stretching, chemical compounds identified are aromatic amines. Absorption band 618 cm^{-1} indicates C-Br group, chemical compounds identified are aliphatic bromo compounds. This FTIR data provides a scientific basis for understanding how chemical modification of the surface of gamal wood can increase interfacial adhesion between wood

particles and cement matrix, reduce water absorption by wood and improve the mechanical performance and durability of the resulting composite mortar.

FTIR spectrum of calcium carbonate (CaCl_2) in Figure 6(c) shows absorption bands related to hydroxyl, ether, and carboxylate groups. The CaCl_2 spectrum shows a peak at wave number $3,432\text{ cm}^{-1}$ with asymmetric O-H stretching (Pongjanyakul and Rongthong, 2010). The H-O-H group at wave number $1,644\text{ cm}^{-1}$ is caused by the presence of water in CaCl_2 (Cho et al., 2014). The use of CaCl_2 in cement can increase the initial binding time with cement paste (De Weerd, 2021). The addition of additives (CaCl_2) to cement can increase workability, and reduce water bleeding during hydration (Dobiszewska et al., 2023). These spectral features are useful for identifying CaCl_2 phases and assessing hydration and dehydration processes via FTIR. The presence of water and Ca-Cl bonds can be clearly distinguished, providing insights into chemical structure and physical state changes of CaCl_2 (Mustapha et al., 2024; Zhao et al., 2024; Kudzin et al., 2025).

The FTIR spectrum of PCC (Cement Portland Composite) in Figure 6(d) shows the hydroxyl group (O-H) spectrum at $3,387\text{ cm}^{-1}$ absorption, C-H groups

at $2,892\text{ cm}^{-1}$ and $2,527\text{ cm}^{-1}$ absorption, C-O groups at $1,797\text{ cm}^{-1}$ and 534 cm^{-1} absorption, and deformed C-H groups at $1,439\text{ cm}^{-1}$ and 883 cm^{-1} . The results of this study are in line with the research of Horgnies et al. (2013). The peak at wave number $3,387\text{ cm}^{-1}$ corresponds to Ca(OH)_2 , which is formed as a silicate phase in cement, and the absorption at $1,500\text{ cm}^{-1}$ to $1,700\text{ cm}^{-1}$ is indicative of the formation of calcium silicate hydrate (CSH) (Ylmen et al., 2009). Key hydration products detected by FTIR include calcium silicate hydrate (C-S-H), portlandite (calcium hydroxide), and calcium carbonate formed during carbonation. FTIR spectra can reveal changes in functional groups and phases, such as the decalcification-polymerization of C-S-H and carbonation effects that influence the mechanical and chemical properties of cementitious materials (Adem et al., 2025; Li et al., 2025).

3.2 Density measurement of mortar composite

The density of composite mortar with the addition of activated carbon and gamal wood chips ranges from $1,950.36 \pm 19.54$ - $2,137.24 \pm 45.09\text{ kg/m}^3$ (Figure 7).

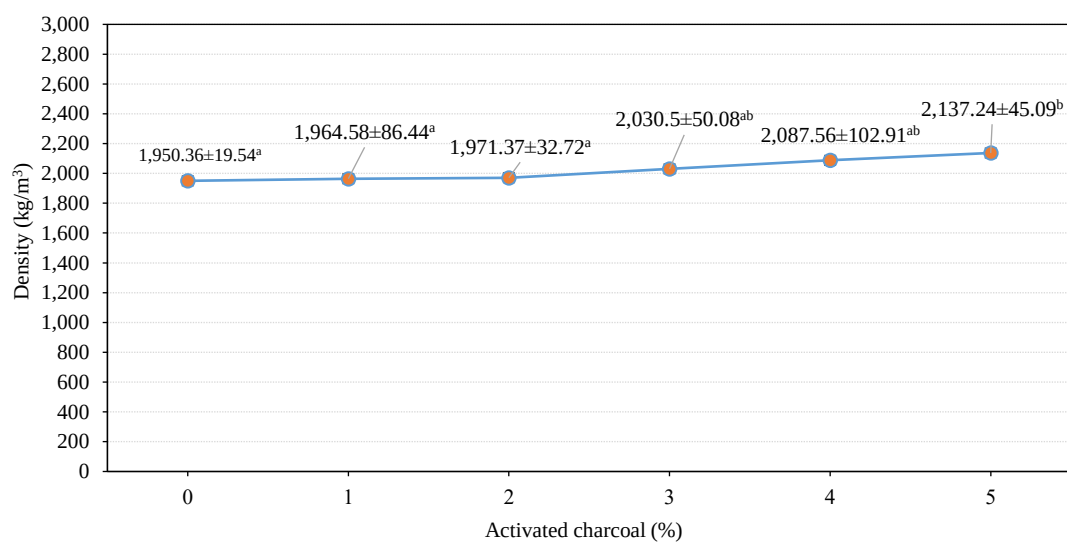


Figure 7. Density measurement of mortar composite

The results of the study showed that the density of the composite mortar increased with the increase in the content of activated carbon. The results of statistical analysis showed that there was a significant difference in the addition of activated carbon to the density of composite mortar. The addition of activated carbon to the cement matrix will make the mortar denser, improving the microstructure of the cement

matrix (Nagrockiene et al., 2017). Research conducted by Mahoutian et al. (2015) explained that the number of air cavities in the mortar will decrease with the addition of 10% activated carbon from the weight of cement. Moon et al. (2017) explained that the hydration process of activated carbon and hydration products that fill the pores of the cement paste, affect the slightly greater density, as seen in this study. Chin

et al. (2020) explained that there was a significant weight reduction in the range of 14% to 27%, with the addition of activated carbon, compared to the density of conventional concrete of $\sim 2,400 \text{ kg/cm}^3$. Wood and rice husk biochars (5%) increased compressive strength by 29% via filler effects and internal curing, implying density stabilization; manure biochar reduced strength and likely density due to coarse particles (Kang et al., 2025). Activated carbon or biochar additions to mortar, often as cement replacements (0.1-24%), noting effects on density, strength, and durability through pozzolanic reactions, filler effects, and internal curing (Wu et al., 2025). The reduction of density in mortars also being affected by the usage of gamal wood chips, where in nature the density of gamal wood chips it self are pretty much lower than common aggregates such as sand.

3.3 Compressive strength of mortar composite

The compressive strength test results of the composite mortar ranged from 8.48 ± 0.76 - 9.71 ± 1.68 MPa (Figure 8). Overall, there was an increase in the compressive strength value with the addition of activated carbon, but with the addition of 5% activated carbon, the compressive strength value decreased. There was an increase in the compressive strength value of 14.57% with the percentage of activated carbon addition of 4%. This phenomenon is attributed to the porous structure of activated charcoal and its capillary adsorption effect, which effectively absorbs free water within the cement mortar, thereby reducing the effective water-to-cement ratio and promoting the formation of a dense cementitious matrix that significantly enhances mechanical strength (Li et al., 2025). The incorporation of activated carbon at a

dosage of up to 4% improves compressive strength through a micro-filler mechanism that densifies the matrix and provides nucleation sites for calcium silicate hydrate (C-S-H) growth; however, at a 5% addition level, strength reduction occurs due to the material's high specific surface area, which absorbs excessive water, thereby inhibiting hydration and increasing porosity.

The inclusion of 1.5% Gliricidia wood chips tends to marginally reduce compressive strength, attributed to the formation of a weak interfacial transition zone between the organic wood particles and the cement paste, as well as the hygroscopic nature of the wood chips that disrupts local hydration, although this adverse effect remains relatively minimal at such a low dosage. The interaction between these materials indicates that the combination of 4% activated carbon with 1.5% wood chips represents the optimal scenario, as the densification benefits of the carbon effectively compensate for the weaknesses introduced by the wood chips, whereas the combination of 5% activated carbon with 1.5% wood chips yields the most pronounced reduction in strength, as the high porosity caused by excess carbon is exacerbated by the weak zones introduced by the wood chips.

The compressive strength value is much greater than without the addition of activated carbon. This shows that increasing the content of activated carbon has an effect on increasing the compressive strength value (Zheng et al., 2017; Swaroop and Raj, 2019). The results of the statistical analysis showed a significant difference in the addition of activated carbon (especially in the addition of 4% of activated carbon) to the compressive strength value of the composite mortar (Figure 8).

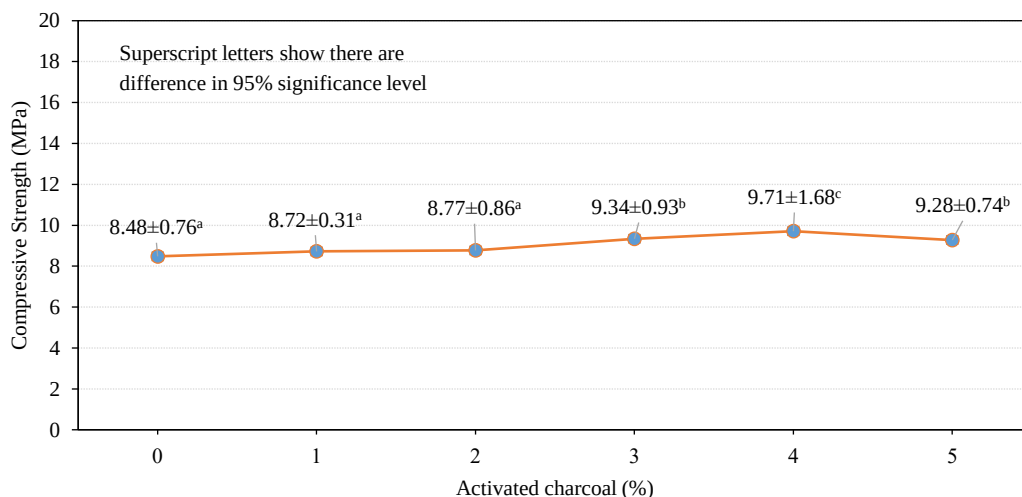


Figure 8. Compressive strength of mortar composite on 28th day curing time

Excessive activated carbon content results in a significant decrease in strength (Na et al., 2021). The compressive strength value of the results of this study decreased by around 4.49% with the addition of 5% activated carbon. The higher compressive strength value in this study can be attributed to the hydration process of activated carbon that fills the pores of the cement paste (Moon et al., 2017). A smaller concentration of activated carbon can accelerate the curing process (Justo-Reinoso et al., 2018). The compressive strength value of the results of this study is in line with previous studies (Chin et al., 2020; Na et al., 2021; Shafigh et al., 2011). Overall, the compressive strength value of the composite mortar from this study is classified as K100 concrete quality which is intended for non-structural concrete (quality $f_c > 8.3$ MPa) according to the standard of SNI 03-2847-2002 (BSN, 2002a).

3.4 Modulus of elasticity and modulus of rupture of mortar composite

The results of the modulus of elasticity (MOE) test of composite mortar ranged from 421.74 ± 69.59 - 645.58 ± 57.51 MPa (Figure 9(a)). With the addition of 4% activated carbon, the MOE was higher than mortar composite without activated carbon, and decreased with increasing activated carbon content. The MOE value tends to be linear with the resulting compressive strength value. This statement is supported by research by Nazari and Riahi, (2011) that there is linearity between the compressive and flexural strength values in mortar or concrete. Based

on Figure 10a, it shows that there is an increase in the MOE value of 53.08% with the percentage of activated carbon addition of 4%, and a decrease of around 32.04% with the addition of 5% activated carbon. The most effective activated carbon content is 4% in practical use and performance (Youn et al., 2009; Khushnood et al., 2015). The results of statistical analysis showed significant difference in the addition of activated carbon to the MOE value. Research conducted by Hermawan et al. (2022) also explains that the MOE value increases with the addition of activated carbon up to 3% of the cement weight.

The results of the modulus of rupture (MOR) test of composite mortar ranged from 2.14 ± 0.27 - 2.75 ± 0.20 MPa (Figure 9(b)), where there was an increase in the MOR value of 28.50% with the addition of 4% activated carbon, and decreased by around 20.73% with the addition of 5% activated carbon. This decrease is due to the proportion of mortar that is not reactive in the cement hydration process. This is in line with the findings in the addition of carbon nanotubes to mortar (Chin et al., 2020). These results show that MOR can increase with the inclusion of activated carbon as a filler in the composite. The results of the statistical analysis showed no significant difference in the addition of activated carbon to the MOR value (Figure 9(b)). The same increasing trend occurred in the compression and MOE tests, meaning that the optimal strength obtained in this study was found in the addition of 4% activated carbon.

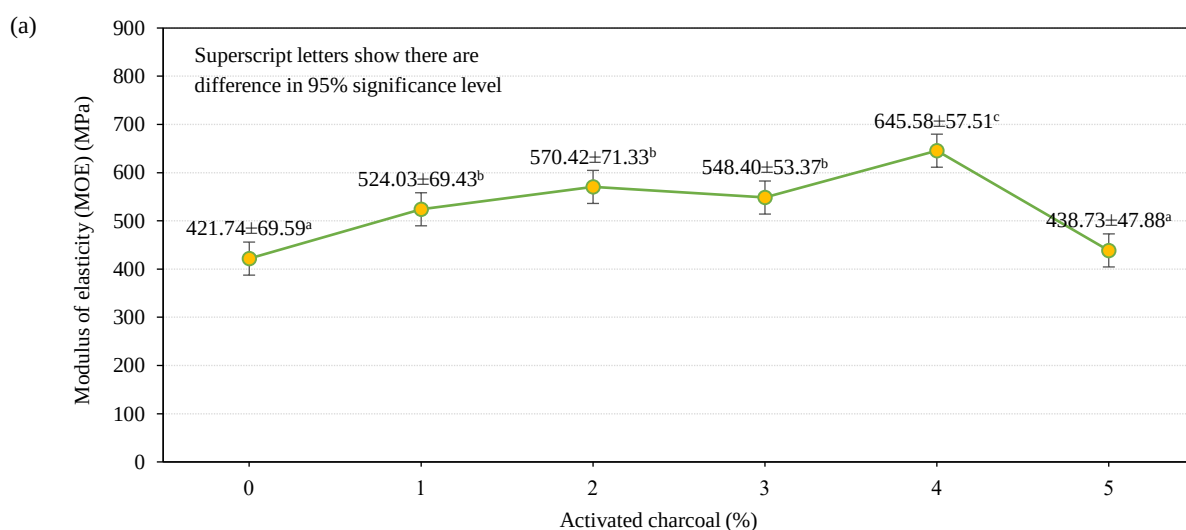


Figure 9. Flexural properties: (a) modulus of elasticity; (b) modulus of rupture

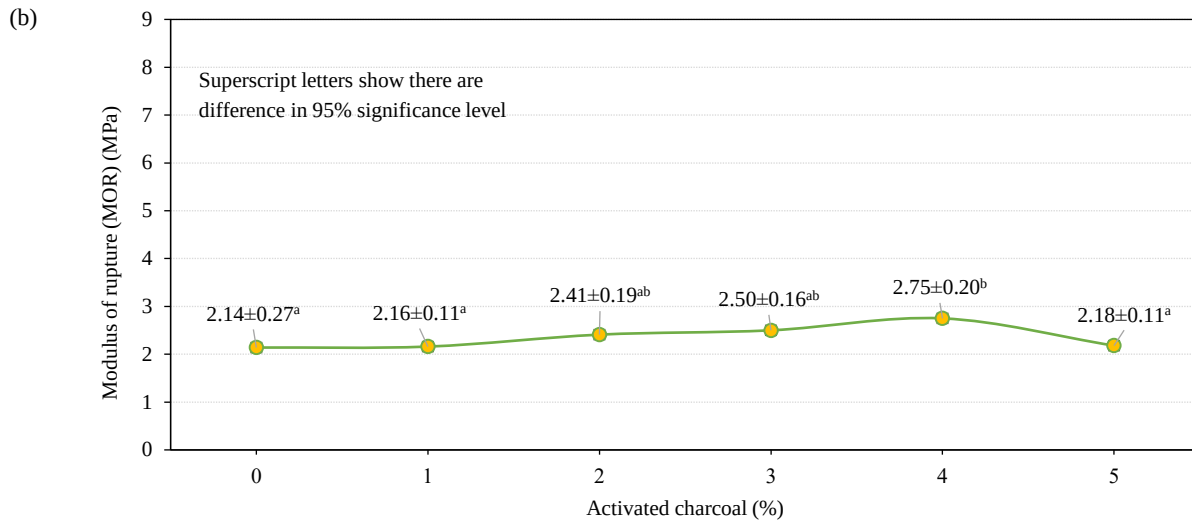


Figure 9. Flexural properties: (a) Modulus of elasticity; (b) Modulus of rupture (cont.)

The addition of 4% activated charcoal by cement weight in the mortar mixture can significantly enhance the Modulus of Elasticity (MOE) and the Modulus of Rupture (MOR) due to the pozzolanic properties of activated charcoal, which is rich in silica and alumina and effectively fills the micro-pores in the mortar's microstructure, thereby strengthening the cement-sand matrix bond (Dias et al., 2025). This improvement is also supported by increased density and durability of the composite mortar, where an optimal composition of 3-4% activated charcoal improves mechanical properties without disrupting the cement hydration process. MOR increases with the amount of activated carbon used, this is related to the hygroscopic nature of activated carbon. The use of more activated carbon will produce more CaCO_3 crystals. The chemicals in these crystals provide mechanical strength to the mortar (Hermawan et al.,

2022). The addition of additives that act as fillers in high-quality concrete affects the MOR value (Salami et al., 2024). The use of activated carbon with a smaller size and smaller proportion will produce stronger mechanical properties.

3.5 Pollutant adsorption percentage of mortar composite

Pollutant adsorption test on composite mortar shows the level of activated carbon's ability to adsorb hazardous pollutant materials based on the SNI 06-3730-1995 (BSN, 1995) standard, on standard test methods for adsorption of benzene, chloroform, and iodine. Pollutant adsorption test of composite mortar includes adsorption of ammonia, benzene, chloroform, and formaldehyde. The results of the pollutant adsorption test can be seen in Figure 10.

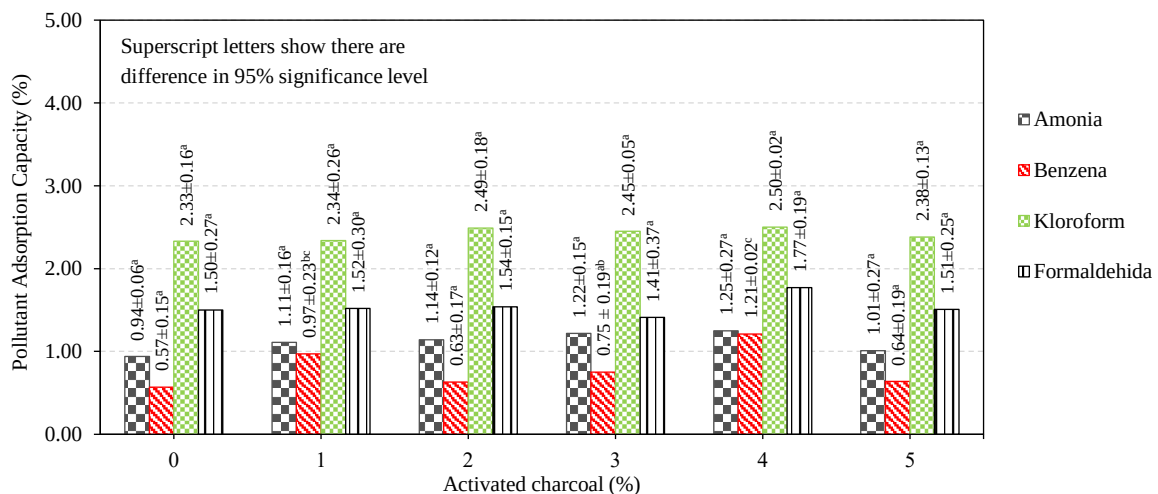


Figure 10. Percentage of pollution adsorption capacity of mortar composite

The pollutant adsorption of composite mortar to ammonia ranges from 0.94 ± 0.06 - $1.25 \pm 0.27\%$. With the addition of 4% activated carbon, the ammonia adsorption is higher compared to mortar composite without activated carbon, and decreases with increasing activated carbon content. The percentage of pollutant adsorption to ammonia is much higher than after being applied to composite mortar. Previous studies reported that the adsorption capacity of activated carbon on ammonia from kenaf stems ranged from 11.21 to 29.78% (Sadir et al., 2022). The results of statistical analysis showed no significant difference in the addition of activated carbon on the ammonia adsorption capacity value. The modification process can result in blockage of the composite mortar's ability to drastically reduce the adsorption capacity (Guo et al., 2005). The ability of composite mortar to adsorb ammonia tends to increase with the amount of activated carbon used. The surface area and pore volume of activated carbon have an impact on the material's capacity to adsorb various contaminants (Budiman et al., 2019).

The adsorption capacity of composite mortar pollutants on benzene ranged from 0.57 ± 0.15 - $1.21 \pm 0.02\%$. With the addition of 4% activated carbon, the adsorption capacity of benzene was higher compared to mortar composite without activated carbon, and decreased with increasing activated carbon content. The percentage of pollutant adsorption capacity for benzene is much higher than after being applied to composite mortar. According to previous studies, the adsorption capacity of benzene by activated carbon from kenaf stems ranges from 10.59 to 13.95% (Sadir et al., 2022). The results of statistical analysis show that there is a significant difference in the addition of activated carbon to the benzene adsorption capacity value (Figure 10). The pores or surface area of activated carbon are directly related to the adsorption value obtained, therefore the larger the surface area of activated carbon, the greater the adsorption capacity (Malini et al., 2023). In addition to reducing the load, activated carbon also functions as an adsorbent when added to mortar, but the low adsorption capacity of mortar is due to the reaction of activated carbon with other components such as cement (Hermawan et al., 2022).

The pollutant adsorption capacity of composite mortar for chloroform ranges from 2.33 ± 0.16 - $2.50 \pm 0.02\%$. With the addition of 4% activated carbon, the chloroform adsorption capacity was higher compared to mortar composite without activated

carbon, and decreased with increasing activated carbon content. The effect of activated carbon formulation on chloroform adsorption capacity is illustrated in Figure 10. The percentage of pollutant adsorption capacity for chloroform was significantly higher than when applied to composite mortar. Previous studies have shown that activated carbon from kenaf stems can adsorb chloroform at a level of 20.5% to 26.72% (Sadir et al., 2022). The results of statistical analysis showed no significant difference in the addition of activated carbon to the chloroform adsorption value (Figure 10). The surface area and pore volume of activated carbon determine its ability to adsorb contaminants (Budiman et al., 2019). The adsorption capacity of activated carbon to chloroform shows that its surface is polar therefore, the higher the adsorption capacity, the more polar molecules remain on the surface of the activated carbon (Jia et al., 2024).

The pollutant adsorption capacity of composite mortar for formaldehyde ranges from 1.50 ± 0.27 - $1.77 \pm 0.19\%$. With the addition of 4% activated carbon, the formaldehyde adsorption capacity is higher than that of mortar composite without activated carbon, and decreases with increasing activated carbon content. The effect of activated carbon formulation on the formaldehyde adsorption capacity is illustrated in Figure 10. The percentage of pollutant adsorption capacity for formaldehyde is much higher than after being applied to composite mortar. Previous studies have reported that the adsorption capacity of activated carbon on formaldehyde from kenaf stems ranges from 15.01-28.26% (Sadir et al., 2022). The results of statistical analysis showed no significant difference in the addition of activated carbon to the formaldehyde adsorption value (Figure 10). The adsorption capacity of formaldehyde is influenced by the chemical properties of the adsorbent surface (Boonamnuayvitaya et al., 2005). The adsorption capacity of formaldehyde in mortar will be greater with the content of activated carbon used (Hermawan et al., 2022). The Adsorption capacity can be strengthened by the addition of activated carbon (Krou et al., 2015). The addition of 0.5% activated carbon in the cement mixture will increase and extend its ability to absorb harmful gases such as NO_x , CO_2 and volatile organic compounds (Horgnies et al., 2015).

Composite mortar incorporating activated carbon demonstrates significant potential for adsorbing benzene pollutants, owing to the porous nature of activated carbon that effectively captures non-polar volatile compounds through physical-

chemical adsorption mechanisms, although specific research remains limited compared to standalone activated carbon studies.

3.6 FTIR characterization of selected mortar composition

The FTIR spectrum of selected composite mortar compositions is presented in Figure 11.

The spectrum of composite mortar with the addition of 4% activated carbon shows a peak at $3,404\text{ cm}^{-1}$ absorption with O-H stretching vibrations (Raki et al., 2004). The CO stretching vibration of carbonate molecules contributes to the other two bands at $1,428\text{ cm}^{-1}$ and 973 cm^{-1} absorption bands. Carbon dioxide and calcium hydroxide in the air combine to produce

carbonate molecules (Yilmaz and Olgun, 2008; Choudhary et al., 2020; Bhat and Debnath, 2011). This condition is consistent with one of the progressive transitions of mortar constituents, where moisture and atmospheric carbon dioxide cause portlandite to change to calcite during the setting process (Chang and Chen, 2006). With increasing nano-silica content, these bands were observed to move towards the lower wavenumber side of $1,428\text{ cm}^{-1}$. CaCO_3 formation in carbonated cement mortar, revealing portlandite consumption and C-S-H decalcification-polymerization effects from additives (Mohanraja and Sharma, 2025). FTIR indications of CaCO_3 production were observed in line with the morphological data identified by FE-SEM.

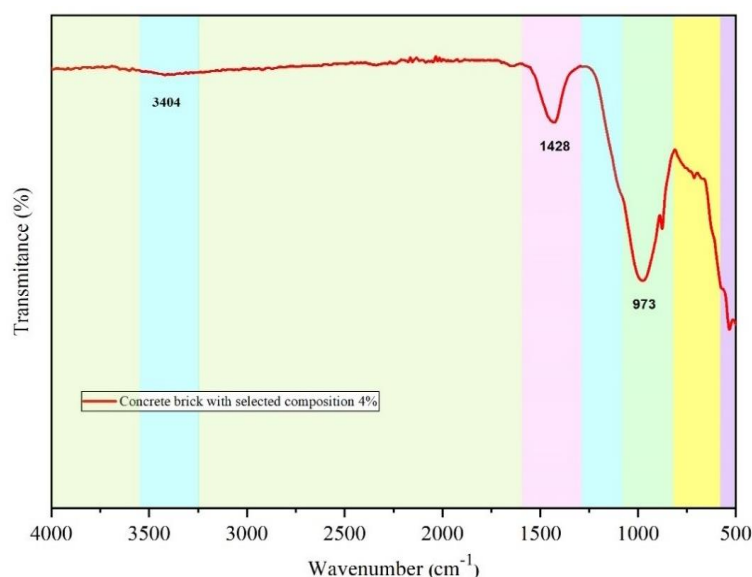


Figure 11. FTIR Spectra of selected mortar composite reinforced with 4% of activated carbon and 1.5% gamal wood chips

3.7 Morphological analysis of selected mortar composite using FE-SEM

Exploring the diversity of morphology, growth mechanisms, and crystal forms of CaCO_3 in cement can be done through scanning electron microscopy (FE-SEM). FE-SEM is another important step in the process of microscopic characterization of mortar. Figure 12 shows the results of observations using FE-SEM with selected compositions and different magnifications.

Figure 12(a) shows that the hydration process of cement with wood occurs optimally by the appearance of CSH bonds. This is indicated by the formation of calcium carbonate (CaCO_3) crystallization (Figure 12(b)). On the other hand, there are irregularly shaped pores (Figure 12(b)), which can affect the bonding of cement with particles. The degree of crystallinity of

the binder (cement) increases, forming well-identified crystals, namely CaCO_3 (white crystal aggregate). The same findings on the compressive strength, MOE, MOR and FTIR analysis show that the addition of activated carbon can increase the optimal strength of the mortar (Hermawan et al., 2022).

The morphology of CaCO_3 crystals can vary under different conditions, such as cubes, prisms, spherical aggregates, and other irregular calcite shapes (Falini et al., 2009). The observed CaCO_3 crystals are mostly granular and aggregated together (Li et al., 2021; Liu et al., 2021). Overall, the formation of CaCO_3 can affect cement-based materials, such as increasing compressive and flexural strength and reducing atmospheric carbonation of the hydrated cement matrix (Savija and Lukovic, 2016).

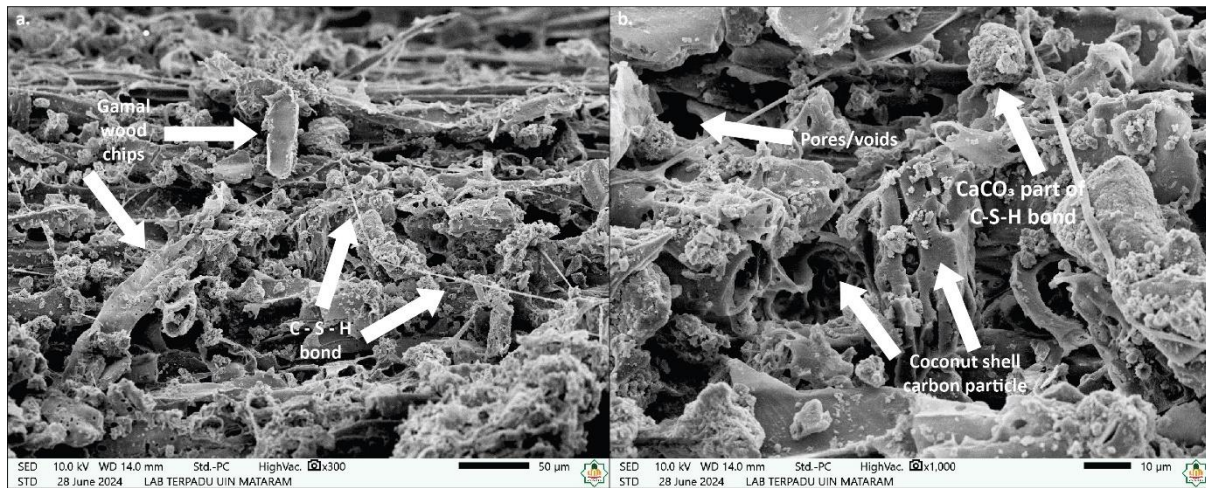


Figure 12. Morphological image of mortar composite reinforced with 4% activated carbon and 1.5% gamal wood chips

In addition, the compatibility of raw materials has a significant impact on crystal morphology and microstructure (Lu et al., 2022). The presence of magnesium and potassium in cement raw materials can affect crystallization. The presence of K ions functions to control the morphology of CaCO_3 crystals and stabilize the surface (Falini et al., 2009). The EDX data showed that CaCO_3 crystals were granular and evenly gathered throughout the identified area (Figure 13).

These results also indicate that variations in the concentration and type of oxygen functional groups play an important role in the reaction. Reactions containing calcium, calcium hydrate, and calcium silicate hydrate function to form CaCO_3 crystals (Yaseen et al., 2019). With elemental mapping (Al, Ca, Si) visualized CaCO_3 precipitation in carbonated mortar, showing refined microstructures (Li et al., 2024; Chylinski et al., 2025).

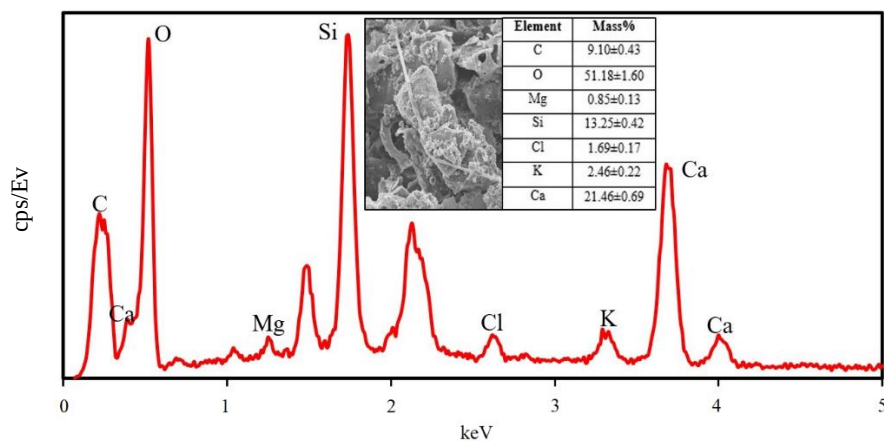


Figure 13. EDX data of mortar composite reinforced with 4% activated carbon and 1.5% gamal wood chips

4. CONCLUSION

The addition of activated carbon to composite mortar did not significantly affect mechanical strength, including compressive strength, MOE, and MOR. The compressive strength value of composite mortar from this study was classified as K100 concrete quality which is intended for non-structural concrete (quality $f_c > 8.3$ MPa). The percentage of 4% activated carbon addition can increase mechanical strength ranging from 14.57-53.08%, and decreased by around

4.49-32.04% with the addition of 5% activated carbon. This decrease is due to the proportion of mortar that is not reactive in the cement hydration process. Overall, the addition of 4% activated carbon to composite mortar can increase mechanical strength.

The addition of activated carbon to composite mortar did not significantly affect the adsorption capacity of ammonia, chloroform and formaldehyde, but significantly affected the adsorption capacity of benzene. Overall, the pollutant adsorption capacity of

composite mortar ranged from 0.57-2.50% or below 3%. The percentage of pollutant adsorption capacity is much higher than after being applied to composite mortar. The low pollutant adsorption capacity of composite mortar is caused by the reaction of activated carbon with other components such as cement, which results in the closure of the activated carbon pores.

The spectrum of composite mortar with the addition of 4% activated carbon shows a peak at $3,404\text{ cm}^{-1}$ absorption with O-H stretching vibrations. The CO stretching vibration of carbonate molecules plays a role in the other two bands at $1,428\text{ cm}^{-1}$ and 973 cm^{-1} absorption bands. Carbon dioxide and calcium hydroxide in the air combine to produce carbonate molecules. Morphological observations as analyzed by FE-SEM, were found to correlate with FTIR analysis, namely the formation of CaCO_3 . The addition of activated carbon can produce more CaCO_3 .

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AUTHOR CONTRIBUTIONS

All authors were involved as main contributors of this research. Baiq Mirawati and Muhammad Sadir conducted the experiments, and prepared the research manuscript. Albert Hendriko assisted in research instrumentation, processed research data, and prepare the research manuscript. I Gde Adi Suryawan Wangiyana, Ismail Budiman, Dede Hermawan, Gustan Pari, and Ariadne Lakshmidevi Juwono supervised the research, designed the experimental design, research methodology.

DECLARATION OF CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the authors but restrictions apply to the availability of these data, which were used under license from the Department of Forestry, Faculty of Engineering and Applied Sciences, Universitas Pendidikan Mandalika; Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Indonesia; and Research Center for Biomasses and Bioproducts, Badan Riset dan Inovasi Nasional for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request.

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