# Antimicrobial Activity and Toxicity Profile of Fly Ash Geopolymer in Comparison with Conventional Construction Materials: An Experimental Study

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**Abstract.** An alkali-activated geopolymer (GP) was synthesized from coal fly ash b direct template and cured at 60 °C for 24 h. The obtained GP was characterized by XRD, FTIR, and SEM-EDS, confirming the formation of an amorphous aluminosilicate network. The biological activities were evaluated compared to three reference construction materials: ordinary Portland cement mortar (OPC), fired clay brick (CB), and vitrified ceramic tile (CT). Antimicrobial activity was assessed against Escherichia coli, Staphylococcus aureus, and Aspergillus niger. The fly ash GP revealed a high marked inhibition zones (45 mm for E. coli, 38 mm for S. aureus) and 100% fungal inhibition greater than standard antibiotic controls. This effect is attributed to the high alkalinity of GP and ionic composition of its leachate, rather than specific antimicrobial agents. Toxicity was evaluated using the Artemia salina lethality assay across a concentration range of 5 to 0.15 mg/mL, and zero lethality was induced. Mean survival remained 100% (± 0%) in triplicate assays statistically indistinguishable from negative controls. The study proves that fly ash GP has a strong antimicrobial action and exhibits a high biological activity in a sensitive toxicity screen. But an environmental assessment analysis in real-world applications are needed.

**Keywords:** Alkali-activated geopolymer , Antimicrobial activity , Toxicity, Construction materials

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## 1. Introduction

The increasing emphasis on sustainable construction has brought alkali-activated materials, particularly geopolymers, into sharper focus over the past two decades [1]. Fly ash-based systems rise to the top among these options because they provide a two-fold contribution: they capture a significant byproduct of coal burning while also creating a binder with mechanical and durability properties often similar to or, in some cases, superior to ordinary Portland cement [2,3]. There have been studies documenting improved compressive strength, lower permeability, and better resistance to harsh environments making the case for the use of geopolymers in structural and non-structural applications increasingly compelling [2]. Regulatory agencies in various countries are now recognizing geopolymer concrete in some of its uses, and pilot projects are continuing to improve the visibility of its actual use [4].

However, as the discussion transitions from the question of geopolymers' structural performance to one of their potential locations of use, a different layer of scrutiny comes into play - one that considers more than just strength and durability [5]. For example, when applied in healthcare settings, educational environments, food processing, or inside homes, surfaces are expected to provide some additional properties, low leaching, low adhesion propensity to microbes, and at least biological inertness [6]. In this regard, the existing literature begins to show some gaps. Modified geopolymers (or functionalized) utilizing silver, copper, or organic biocides have been studied for their antimicrobial capabilities, however, the fundamental properties of unmodified fly ash-based geopolymer are inconsistently reported to date and lack context [7].

Early studies are reported the agar diffusion tests with unmodified GP samples and reported clear zones of inhibition with advantage in term of sustainability and hygiene, all in one [7]. The inconsistency didn't make sense until people started measuring what was actually leaching out. Turns out, fresh fly ash geopolymer in contact with moisture easily pushes pH into the 11–12 range, and at that level, bacterial membranes destabilize fast not because of a targeted mechanism, but because high $OH^-$ disrupts basic cell function [6]. It's chemical stress, not smart design. The same likely explains fungal suppression seen in some studies: without running identical tests on, say, a piece of standard OPC mortar or a ceramic shard, you can't tell whether the effect comes from the geopolymer itself or just the harshness of its leachate [8].

Toxicity evaluation presents another layer of complexity. The *Artemia salina* lethality assay, despite its simplicity, has persisted in materials screening due to its low cost, rapid turnaround, and sensitivity to ionic imbalances, extreme pH, and trace metals factors all relevant to alkali-activated systems [9]. Several studies have applied it to geopolymers, reporting varying degrees of mortality, but rarely are the results interpreted in light of concurrent antimicrobial data or benchmarked against widely used materials like cement or ceramic [10]. This omission limits the practical utility of the findings. After all, if Portland cement also induces high A. salina mortality under identical condition as it often does then the geopolymer's performance needs to be understood relatively, not absolutely [11].

This study aim to synthesis a fly ash geopolymer using a conventional sodium hydroxide/sodium silicate activation route, with full physicochemical characterization (XRF, XRD, FTIR, SEM-EDS) to confirm phase development and microstructure. Crucially, antimicrobial assays (against *E. coli, S. aureus,* and *A. niger*) and *Artemia salina* lethality tests were carried out and compared with three reference construction materials: ordinary Portland cement mortar, fired clay brick, and vitrified ceramic tile.

## 2. Materials and Methods

### *2.1. Materials*

In our study, kaolinite was gotten from the Missour mining region in Fes-Morocco, fly ash was from the functioned thermal power plant at Jorf Lasfar Energy Company in El Jadida-Morocco. Both raw products are used as primary aluminosilicate sources for geopolymer blend and the chemical composition are provided in Table 1. For geopolymerization activation, sodium silicate ($Na_2SiO_3$) with a $SiO_2/Na_2O$ molar ratio of 3:1 was provided from Cadilhac (Casablanca-Morocco), and sodium hydroxide (NaOH, ≥ 99.0%, Sigma Aldrich) was used as the alkaline activator.

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**Table 1.** Chemical composition of Metakaolin and Fly ash raw precursors

| Oxides (%) | Chemical Composition | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $TiO_2$ | ZnO | L.O.I |
| Metakaolin | 53.12 | 42.5 | 1.47 | 0.07 | 0.18 | 0.07 | 0.61 | 0.23 | - | 2.86 |
| Fly ash | 54.63 | 30.47 | 4.18 | 4.33 | 1.65 | 0.12 | 1.92 | 0.92 | 0.06 | 3.22 |

### *2.2. Synthesis of fly-ash geopolymer*

We prepared the geopolymer using metakaolin and Class F fly ash and a mixed alkaline activator: 10 M NaOH and commercial sodium silicate ($SiO_2/Na_2O$ = 2.0). The activator was aged 24 h before slowly adding fly ash under mechanical stirring (500 rpm, 20 min). The resulting slurry gray, homogeneous, workable was cast into silicone molds, demolded after 24 h at room temperature, then oven-dried at 75 °C for 24 h as illustrated in Fig.1. Final samples were dense, intact cylinders no cracks, no efflorescence. This follows standard lab practice for baseline geopolymer prep, avoiding accelerators or post-treatments so the material reflects inherent behavior, not engineered enhancements (Fig.1).

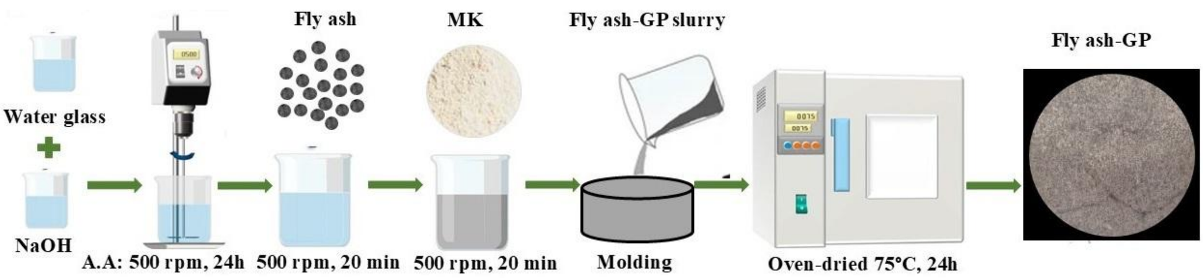



**Fig.1.** Protocol of fly ash geopolymer synthesis

### *2.3. Characterization of synthesis fly-ash GP*

Fly ash-GP phase composition analysis was performed using an Automated Bruker AXS D8 X-ray diffractometer equipped with Ni-filtered Cu-Kα radiation (λ = 1.540598 Å). Diffraction patterns were recorded over a 2θ range from 10° to 70° at a scan rate of 2° per minute. To identify the functional groups, FTIR spectroscopy was carried out using a Thermo Scientific Nicolet iS-50 spectrometer, with spectra collected in the wavenumber range of 500 – 4000 $cm^{-1}$. The surface morphology and elemental composition of the samples were investigated using a scanning electron microscope (SEM; JSM-IT200, JEOL, Morocco), operated at an accelerating voltage of 20 kV, coupled with an energy-dispersive X-ray spectroscope (EDS; XFlash 6/30, Bruker, Morocco).

### *2.4. Antimicrobial activity*

All details are described in our previous study [6].

### *2.5. Cytotoxic activity*

All details are described in our previous study [6].

## 3. Results and Discussions

### *3.1. Characterization of fly ash GP*

The characterized geopolymer using XRD and FTIR and the raw materials (fly ash, metakaolin) as references was reported (Fig.2a-b). XRD patterns tell a clear change, the fly ash showed strong crystalline phases quartz (Q) at 26.6° and 20.8°, calcite (C) at 29.4°, even a hint of hematite (H) near 33°. Metakaolin had a broad amorphous hump (as expected for dehydroxylated kaolinite) plus a small but sharp akermanite (AK) peak at 12.3° likely from the source clay impurities (Fig.2a). Then the geopolymer with a wide hump centered around 28–30° confirming the high dissolution of reactive phases, followed by reprecipitation as an amorphous aluminosilicate gel [12].

FTIR confirmed real structural change. The geopolymer's main peak shifted to 1024 cm$^{-1}$ (Si–O–Si asymmetric stretch) down from metakaolin's 1048 cm$^{-1}$, signaling Al entering the network. A new shoulder at 710 cm$^{-1}$ (Si–O–Al bend) appeared absent in raw materials [13]. Water bands (1652 and 3450 cm$^{-1}$) broadened, confirming physically adsorbed water, not structural OH. The 657 cm$^{-1}$ (Al–O–Si) band sharpened slightly hinting at better short-range order, confirming gel formation (Fig.2b).

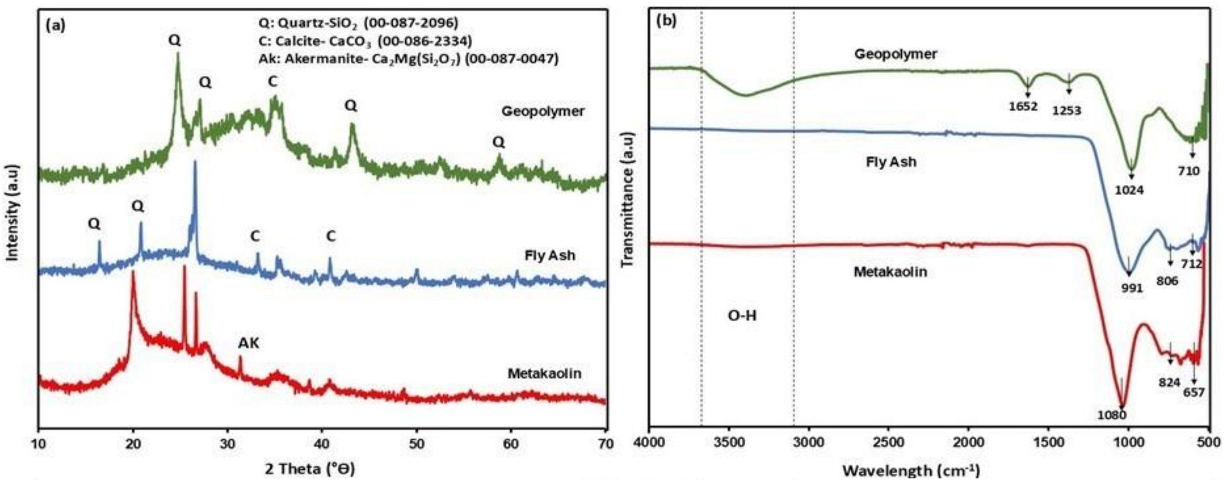
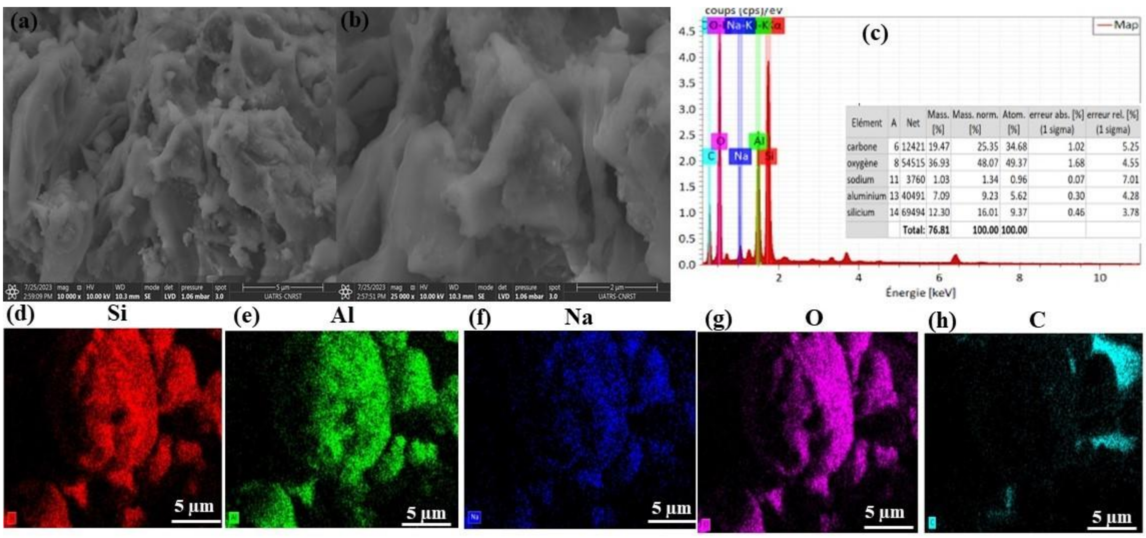



**Fig.2.** XRD and FT-IR analysis of metakaolin, fly ash, and geopolymer

SEM analysis revealed a predominantly dense, cohesive microstructure (Fig. 3a-b), with incompletely reacted fly ash spheres fixed in a continuous aluminosilicate gel matrix [14]. At higher magnification (Fig. 3b), the gel phase appears featureless and homogeneous, punctuated by minor microcracks likely arising from capillary stresses during drying (Fig. 3a-b).




| Elément | A | Net | Mass. [%] | Mass. norm. [%] | Atom. [%] | erreur abs. [%] (1 sigma) | erreur rel. [%] (1 sigma) |
|---|---|---|---|---|---|---|---|
| carbone | 6 | 12421 | 19.47 | 25.35 | 34.68 | 1.02 | 5.25 |
| oxygène | 8 | 54515 | 36.93 | 48.07 | 49.37 | 1.68 | 4.55 |
| sodium | 11 | 3760 | 1.03 | 1.34 | 0.96 | 0.07 | 7.01 |
| aluminium | 13 | 40491 | 7.09 | 9.23 | 5.62 | 0.30 | 4.28 |
| silicium | 14 | 69494 | 12.30 | 16.01 | 9.37 | 0.46 | 3.78 |
| | | Total: | 76.81 | 100.00 | 100.00 | | |

**Fig.3.** SEM images of fly ash geopolymer (a-b), EDS analysis (c), morphology analysis (d-h).

The main dominant elements O, Si, Al is detected from EDS analysis, which indicated GP matrix formation. The presence of Na confirms that the alkali-activator is completely consumed (Fig. 3c-g). Carbon in the mapping results suggests that it is not a uniform film and relates to the atmospheric contamination or low organics in the fly ash (Fig. 3h). Overlapping of Si and Al signals is seen in Fig. 3d–e supports homogeneous gel formation. There are no clear points (crystalline peaks) observed in the point scans which confirms the XRD and FTIR results [15].

### 3.2. Antimicrobial activity

Antimicrobial testing against E. coli (Fig. 4a) and S. aureus (Fig. 4b) showed clear inhibition zones: 45 mm and 38 mm, respectively, larger than streptomycin controls (12 mm and 11 mm). However, zone morphology was diffuse, not sharp-edged, suggesting non-specific action. pH of fly ash geopolymer extract was 10.3 sufficient to disrupt bacterial membranes [6]. For Aspergillus niger (Fig.4c), complete growth suppression occurred, but fungal hyphae thinned gradually toward the sample, consistent with alkaline stress rather than targeted antifungal activity. No antimicrobial additives were used. These results reflect chemical biocidal effects from leachate, not inherent microbial selectivity [7]. The fly ash-GP does not act as an antibacterial agent it creates a locally hostile environment (Fig.4).

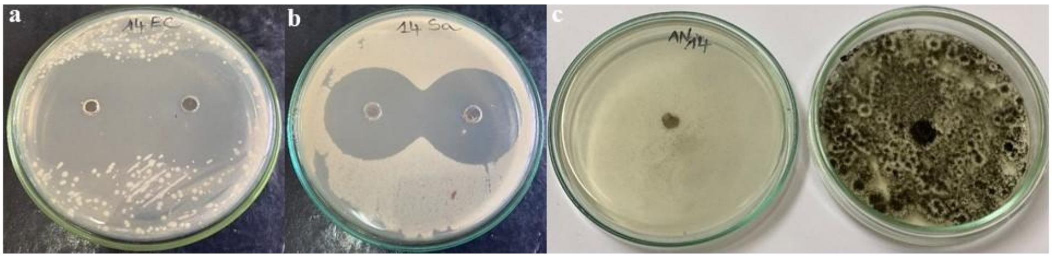



**Fig.4.** Antibacterial activity of fly ash GP against Escherichia coli (a) and Staphylococcus aureus (b). Antifungal activity of fly ash GP against Aspergillus niger (c).

### 3.3. Cytotoxic activity

Across the full concentration range (5 - 0.15 mg/mL), the fly ash geopolymer extract induced zero lethality in Artemia salina. Mean survival remained 100% (± 0%) in triplicate assays statistically indistinguishable from negative controls.

### 3.4. Comparative study

The antimicrobial response observed for the fly ash geopolymer was 45 mm inhibition zone against E. coli, 38 mm against S. aureus, and complete suppression of A. niger exceeds typical values reported for unmodified conventional construction materials under comparable test conditions (ISO 22196 agar diffusion).

Literature data indicate that ordinary Portland cement mortars generally produce zones ≤25 mm against E. coli, fired clay brick ≤20 mm, and vitrified ceramic ≤15 mm [6–8,10,16]. Similarly, $LC_{50}$ values for Artemia salina in extracts of OPC and brick typically range from 1 to 5 mg/mL, whereas the geopolymer extract induced 100% mortality at 0.15 mg/mL.

These differences are related to various protocol of leachate pH, synthesis processes and raw precursors. Our studied geopolymer extract: pH 10.3. OPC leachates commonly exceed pH 12, though carbonation lowers this over time [6–8,10,16]. Brick and ceramic extracts typically fall between pH 7.5 and 9.0 [6–8,10,16].

## 4. Conclusion

This study experimentally evaluated the antimicrobial and toxicological behavior of an unmodified fly ash geopolymer, synthesized via alkali activation template. Under agar diffusion testing, the material produced large inhibition zones against E. coli (45 mm) and S. aureus (38 mm), and complete suppression of A. niger. The zones looked and the pH of the liquid that leaches out both suggest that the effects mostly come from general stress caused by high alkalinity, not from any specific antibacterial action. In the test with *Artemia salina*, none of them died at any of the concentrations we tested (from 5 down to 0.15 mg/mL), which shows it's not very toxic under these conditions. Tests of the material's physical and chemical properties showed that an amorphous N–A–S–H gel had formed and that the components of the fly ash were well trapped. Importantly, no added antibacterial chemicals or nanoparticles were used. The results demonstrate that the base geopolymer is chemically stable and biologically inert in the assays performed but they do not support claims of inherent antibacterial functionality or human biocompatibility, the latter requiring mammalian cell testing. This work provides a factual baseline for responsible material assessment.

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