Development of Multifunctional Polyurethane Composites With Synergistic Flame Retardancy, Thermal Insulation, and Controlled Antimicrobial Activity

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This study presents the development of multifunctional polyurethane (PU) composites combining flame retardancy, thermal insulation, and antimicrobial activity through the incorporation of expandable graphite (EG), FeMg–BDC-based material, and silver nanoparticles (AgNPs). Structural characterization confirmed the successful integration of all components into the PU matrix. Thermal analysis showed that pure PU exhibited a low thermal conductivity of 0.021 W/m·K. The addition of EG increased this value to 0.053 W/m·K, while further incorporation of FeMg–BDC and AgNPs reduced it to 0.039–0.041 W/m·K, indicating improved heat insulation due to disruption of heat transfer pathways. Flame retardancy testing demonstrated that the optimized composite (PU-04) achieved a UL-94 V-0 rating, a limiting oxygen index (LOI) of approximately 31%, and a char residue above 22%, confirming significantly enhanced fire resistance. Antimicrobial results showed that only AgNP-containing samples exhibited activity. After 48 hours, PU-03 produced inhibition zones of 0.8–1.1 cm against Escherichia coli and Staphylococcus aureus, and 1.2–1.8 cm against Aspergillus fumigatus and Penicillium digitatum. In contrast, composites designed for controlled Ag+ release exhibited more sustained antimicrobial effects, with inhibition zones reaching 1.5–2.6 cm over extended time. Release studies confirmed gradual Ag+ release up to 85–90% at pH 5 after 120 hours, compared to faster release in non-controlled systems. These findings demonstrate a synergistic strategy for designing advanced polymer composites with simultaneous fire resistance and long-term antimicrobial activity, offering strong potential for applications in construction, healthcare, and protective environments.

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