



Research article

Ramp rate-controlled mineralogical evolution and multi-scale structure–property framework for arsenate removal in nanohematite-bearing clay ceramic water filters

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ABSTRACT

Sintering kinetics govern phase evolution and structure–property relationships in clay-based ceramics, yet the influence of heating rate on mineralogical evolution and filtration performance remains poorly understood. Here, ferruginous clay ceramic water filters were used to develop a multi-scale process–structure–property framework linking sintering ramp rate to mineralogical restructuring, hematite crystallographic evolution, transport behaviour, and arsenate removal. The raw clay contained high Fe_2O_3 (28.22wt.%) and an intrinsic nanohematite phase (RHPA = 18.26%, $D = 12.43\text{nm}$), providing an in-situ iron oxide phase relevant to arsenate adsorption. Ramp rate regulated hematite abundance and crystallographic characteristics, while multi-criteria optimisation integrating porosity, transport performance, densification, structural integrity, and hematite reactivity identified an optimum ramp rate of 4°Cmin^{-1} . Under these conditions, arsenate concentrations were reduced from 22.70 ± 1.50 to $9.91 \pm 0.34\mu\text{g L}^{-1}$ (56.3% removal), achieving compliance with WHO guidelines. Zeta potential measurements revealed a transition from a strongly negative surface charge in the raw clay ($-32.1 \pm 1.4\text{mV}$) to a near-neutral charge in the optimised filter ($+1.3 \pm 0.2\text{mV}$), consistent with arsenate adsorption occurring predominantly through inner-sphere interactions on hematite-bearing surfaces. The optimised filter retained $92.9 \pm 2.6\%$ of its flexural strength after prolonged aqueous exposure, indicating good structural stability. These findings establish sintering ramp rate as a key design parameter governing the evolution and performance of ferruginous ceramic filtration materials.

1. Introduction

Arsenic contamination of drinking water remains a critical global public health challenge, with chronic exposure linked to severe health risks including cancer, even at low concentrations [1,2]. Although the World Health Organization (WHO) guideline is $10\mu\text{g L}^{-1}$, exceedances are widely reported in groundwater systems, with concentrations up to several thousand $\mu\text{g L}^{-1}$ depending on hydrogeochemical conditions [3]. Extreme localized occurrences have been documented, including concentrations up to 3.5mg L^{-1} in specific Ugandan water sources [4] and $535.1\mu\text{g L}^{-1}$ in Argentine groundwater [5], highlighting strong spatial variability. Even low-level exposure ($\sim 10^{-2}\text{mg L}^{-1}$) can exceed acceptable carcinogenic risk thresholds [6], underscoring the need for

affordable and effective household treatment technologies. Clay-based ceramic water filters offer a promising low-cost solution; however, their performance remains inconsistent because processing-induced changes in mineralogy, microstructure, and surface reactivity can influence both transport and adsorption behaviour [7,8].

Sintering of ceramic systems is a multi-scale process involving particle rearrangement, viscous flow, phase transformation, pore evolution, and crystallographic evolution, which collectively govern mineralogical development, transport behaviour, and functional performance [9–11]. While these processes govern densification and permeability, their influence on reactive mineral phases, particularly iron oxides in ferruginous clays, remains insufficiently understood. Hematite is a key reactive phase for arsenate adsorption, but its performance depends strongly on

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