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THE EFFECT OF PORE CONFIGURATION IN DEGRADATION OF POROUS FE

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ABSTRACT

Biodegradable bone scaffolds are crucial in orthopedic applications, offering mechanical support while gradually degrading to allow natural bone regeneration. Iron (Fe), known for its high mechanical strength, suffers from a low degradation rate, making its application as a bone scaffold material challenging. This study investigates the influence of pore configuration on the degradation rate of porous iron fabricated to a consistent porosity of 55%. Two configurations, 2x2 and 3x3, were developed by varying the hole diameters while maintaining equivalent porosity. The degradation behaviour was evaluated through a dynamic immersion test in phosphate-buffered saline (PBS) for 7, 14, and 28 days. Results showed that the 3x3 configuration, with higher surface area, exhibited a greater degradation rate. This outcome underscores the role of pore architecture, particularly surface area and shear stress dynamics, in controlling degradation rates of iron-based scaffolds.

KEYWORD

Porous iron, degradation rate, bone scaffold, pore configuration, dynamic immersion, biodegradable metals

INTRODUCTION

Bone scaffolds are pivotal in addressing orthopedic complications by providing a temporary structure that supports bone regeneration. Globally, the demand for effective bone scaffolds is surging, with the market projected to grow from USD 3 billion in 2023 to USD 5.4 billion by 2032 (Farajpour et al., 2024). Materials used in scaffold design must be biocompatible, mechanically robust, osteoconductive, and degradable at a rate matching bone healing (Md Saad et al., 2016).

Iron (Fe) is a promising candidate due to its strength and biocompatibility; however, its low degradation rate poses a major hurdle (Sharma & Pandey, 2019). Researchers have explored porous architectures to increase Fe's degradation by enhancing fluid interaction and surface area (Li et al., 2019). Yet, previous studies primarily focused on varying porosity levels without isolating the effect of pore configuration at constant porosity.

This research examines how pore configurations with identical porosity but differing surface areas influence degradation rates. By simulating physiological conditions using dynamic immersion testing, we aim to quantify the degradation behaviour and derive insights for scaffold optimization.

MATERIAL AND METHODOLOGY

Porous Fe specimens were machined from 99.8% pure Fe rods (25.4 mm diameter) into uniform chips of 10.2 mm × 10.2 mm × 2.2 mm. Two pore configurations were fabricated: a 2x2 layout and a 3x3 layout, both adjusted to achieve 55% porosity.

The degradation behaviour was evaluated using a dynamic immersion system, which more accurately replicates physiological conditions than static setups. The samples were immersed in phosphate-buffered saline (PBS) at a constant temperature of 36 ± 0.5°C, maintained using a controlled water bath. The solution was circulated using a peristaltic pump at a flow rate of 0.3 ml/min to simulate shear forces exerted by bodily fluids. Each configuration was tested over 7, 14, and 28-day intervals. The setup simulated physiological shear stress experienced in vivo.

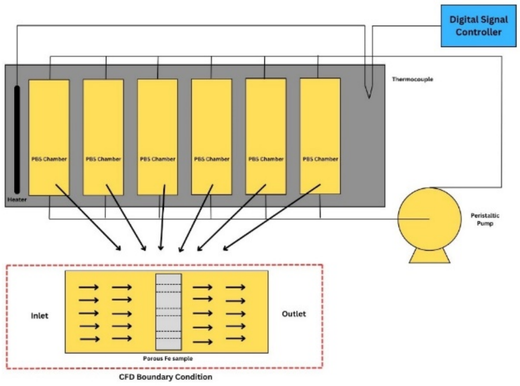

Figure 1: Schematic diagram of dynamic immersion test rig.

Scanning Electron Microscopy (SEM) was employed to examine the surface morphology of the corroded samples at various magnifications, revealing microstructural changes and pitting effects. Energy Dispersive X-ray Spectroscopy (EDX) was conducted to identify elemental composition on the surface, focusing on iron, oxygen, and potential phosphate compounds resulting from immersion in PBS.

Upon completion of each immersion period, the specimens were immersed in 1.0 M hydrochloric acid (HCl) with 0.7 g of hexamethylene tetramine for 10 minutes and subsequently ultrasonically cleaned with an ultrasonic cleaner to further remove the corrosion products effectively.

Degradation rates were determined using weight loss measurements, where Wo is the final weight (mg) and Wi is the initial weight (mg). Then the weight loss of porous Fe was calculated the equation 2 with taking into consideration the rate of weight loss per unit area with time, Wm, where A is area exposed to solution, T is time of immersion day. The degradation rate (mg cm-2 d-1) was then converted to Pm, degradation rate (mm/y) using equation 3, where ρ is density of the iron.

$$\Delta W_{\%} = \frac{W_i - W_o}{W_i} \quad (1)$$

where:

$\Delta W_{\%}$	: Weight loss percentage (%)
W_i	: Initial weight (mg)
W_o	: Final weight (mg)

$$\Delta W_m = \frac{W_i - W_o}{AT} \quad (2)$$

where:

ΔW_m	: Degradation rate (mg cm^{-2} d^{-1})
W_i	: Initial weight (mg)
W_o	: Final weight (mg)
A	: Area exposed to the solution (cm^2)
T	: Time of immersion (day)

$$P_m = \frac{3.65 \Delta W_m}{\rho} \quad (3)$$

where:

W_m : Degradation rate (mg cm^{-2} d^{-1})

ρ : Density of iron (g cm^{-3})

RESULT AND DISCUSSION

Dynamic immersion test results over 7, 14, and 28 days revealed that the 3×3 configuration consistently degraded at a higher rate than the 2×2 configuration. This difference became more apparent with time, with the 3×3 showing around 20–25% greater degradation by day 28. The early onset of corrosion in the 3×3 samples was likely due to their increased surface area, which allowed more effective contact with the PBS solution (Li et al., 2019; Putra et al., 2024).

The higher number of smaller pores in the 3×3 design not only increased surface exposure but also promoted more uniform corrosion. In contrast, the 2×2 configuration exhibited deeper localized pitting, indicating more uneven material loss. Fluid dynamics also played a role; the 3×3 samples likely experienced greater shear stress around the pore walls, contributing to a disruption of protective film formation and accelerating degradation (Elenskaya et al., 2024; Putra et al., 2024).

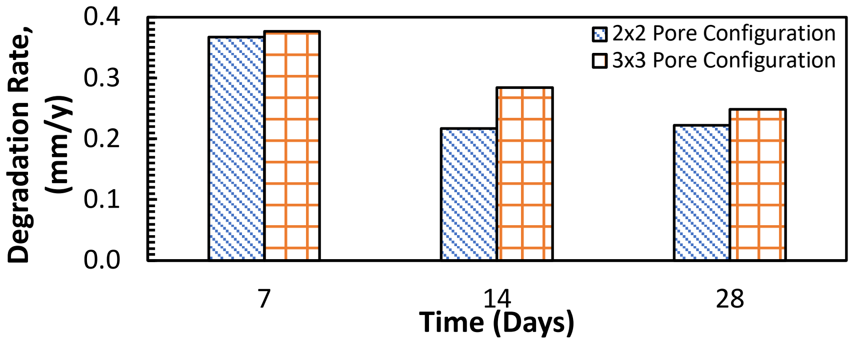

Figure 2: Graph of degradation rate (mm/y) against time (days)

CONCLUSION

This study demonstrated that at constant porosity, pore configuration significantly influences the degradation behaviour of porous iron in dynamic immersion conditions. The 3x3 configuration degraded faster than the 2x2 due to higher surface area and associated shear stress effects. These findings are vital for the rational design of bone scaffolds to match degradation with tissue regeneration timelines.

The data strongly suggest that merely specifying porosity in scaffold design is insufficient—pore arrangement, frequency, and connectivity must also be considered to achieve the desired degradation performance. The increased number of pores in the 3x3 configuration not only enhanced mass transport but also supported a more uniform corrosion profile, which could be advantageous for consistent mechanical performance during biodegradation.

Future studies should expand this investigation to include in vivo environments and mechanical testing to correlate degradation with mechanical integrity over time. Moreover, exploring hybrid materials or surface treatments that complement the degradation process could further optimize iron-based scaffolds for clinical use. Ultimately, this research provides foundational insight for developing tailored scaffold architectures that balance biodegradability and mechanical function in regenerative medicine.

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