Postprint of a Numerical Study on Multi-Field Coupling in Mortar-Aggregate under Microwave Irradiation

Authors: Shao Zhushan

Date: 2026-01-30T23:21:30+00:00

Abstract

The construction of new buildings and the demolition of old ones generate large quantities of waste concrete, and extracting recycled aggregates from waste concrete has become a solution to alleviate the resource crisis and achieve aggregate recycling. Owing to its characteristics of selective heating, high efficiency, and environmental friendliness, microwave heating has been increasingly applied to the recovery of recycled aggregates. To investigate the relationship between interfacial separation of mortar and aggregate under microwave irradiation and the coupling of multiple physical fields, a three-dimensional two-phase mortar-aggregate model was established using COMSOL Multiphysics software, and the distributions of the electromagnetic field, temperature field, and stress field were analyzed. The reliability of the numerical analysis was verified by comparison with microwave heating experiments. The numerical simulation results indicate that the electric field intensity and temperature gradient reach their maximum values at the mortar-aggregate interface; the outer side of the aggregate is subjected to tension, while the inner side is subjected to compression. Under the heating condition of 3 kW for 200 s, the first principal stress at the mortar-aggregate interface exceeds the ultimate tensile strength of the mortar, leading to crack initiation at the interface. As heating time increases, the cracks gradually propagate from the interface toward the specimen edges and coalesce, eventually causing separation of the mortar and aggregate at the interface.

Full Text

Numerical Analysis of Multi-Field Coupling in Mortar-Aggregate Under Microwave Irradiation

Authors: Zhushan Shao[1],[2],[3], Yansong Jiang[2],[3], Wei Wei[1],[3], Yihao Xiao[1]
[1] College of Science, Xi' an University of Architecture and Technology, Xi' an

710055, China
[2] College of Civil Engineering, Xi’ an University of Architecture and Technology, Xi’ an 710055, China
[3] Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, Xi’ an University of Architecture and Technology, Xi’ an 710055, China

Abstract

The construction of new buildings and demolition of old structures generate substantial amounts of waste concrete. Extracting recycled aggregates from waste concrete has emerged as a viable solution for mitigating resource scarcity and achieving sustainable aggregate utilization. Microwave heating, characterized by its selective heating capability, high efficiency, and environmental friendliness, is gradually being applied in recycled aggregate recovery. To investigate the relationship between mortar-aggregate interface separation and multi-field coupling under microwave irradiation, this study establishes a three-dimensional mortar-aggregate biphasic model using COMSOL Multiphysics software. The distributions of electromagnetic field, temperature field, and stress field are analyzed. Numerical reliability is verified through comparison with microwave heating experiments. Simulation results indicate that both electric field intensity and temperature gradient reach their maximum values at the mortar-aggregate interface. Under heating conditions of 3 kW for 200 s, the first principal stress at the interface exceeds the ultimate tensile strength of mortar, initiating interfacial cracking. As heating continues, cracks propagate progressively from the interface toward the specimen edges, eventually interconnecting and causing complete separation between mortar and aggregate.

Keywords: microwave; aggregate; multi-field coupling; temperature; thermal stress

1. Introduction

Global infrastructure development generates enormous demand for construction materials while simultaneously producing vast quantities of demolition waste. Traditional methods for recovering aggregates from waste concrete, including physical grinding, chemical acid treatment, and biological sedimentation, suffer from significant drawbacks such as high noise levels, secondary pollution, and elevated costs. Microwave heating technology, widely adopted in food processing and industrial applications due to its efficiency and uniformity, demonstrates considerable potential for concrete recycling. Previous studies have shown that microwave irradiation damages the mortar matrix surrounding coarse aggregates, accelerating the separation process. For instance, Everaert et al. found that microwave pretreatment (3 kW, 60 s) followed by mechanical processing increased high-quality recycled aggregate yield from 3.5% to 33% compared to mechanical methods alone. Similarly, Lippiatt et al. reported that microwave treatment (2 kW, 2.45 GHz) on a single-mode test bench significantly enhanced aggregate liberation.

While experimental studies have validated the effectiveness of microwave-assisted concrete recycling, accurately measuring internal electromagnetic field distributions, stress evolution, and deformation remains challenging under current experimental conditions. These internal mechanical characteristics are crucial for understanding the mortar-aggregate separation mechanism. Numerical simulation provides an effective solution by enabling accurate analysis of thermal-mechanical responses within the microwave field. This study employs COMSOL Multiphysics to develop a fully coupled electromagnetic-thermal-mechanical model, offering detailed numerical analysis of the separation mechanism during microwave irradiation.

2. Numerical Model Development

2.1 Specimen Model and Microwave Equipment Numerical simulations were conducted using COMSOL Multiphysics. Microwave heating experiments were performed using a CY-MU1000C-L microwave system (Changyi Microwave Technology Co., Ltd.), consisting of a microwave generation system, heating cavity, and external cooling system. The heating cavity connects to a 2.45 GHz WR340 rectangular waveguide. A three-dimensional geometric model was established based on the actual equipment dimensions, with the specimen positioned at the cavity center. Model dimensions are detailed in .

The dielectric properties of materials were measured using a vector network analyzer (PNA37020) with a coaxial probe and support structure via the single-ended open method. Tests were conducted on basalt and mortar specimens across 2.4–2.6 GHz to determine the dielectric constant variation. The obtained dielectric parameters at 2.45 GHz serve as simulation inputs, with other material parameters derived from relevant literature. Numerical simulation parameters for mortar and basalt are summarized in .

2.2 Model Assumptions To ensure computational efficiency while maintaining physical realism, the following assumptions were adopted: - Thermal radiation from the specimen to the surroundings is neglected; model boundaries are assumed thermally insulated - Mortar and basalt models are dense with no internal pores - Both materials are dry, and pressure from water vapor is not considered - Specific heat capacity is treated as constant pressure values - Dielectric parameters and thermal conductivity are temperature-independent constants - Both materials are non-magnetic, ignoring magnetic field coupling effects - For solid mechanics fields, the specimen bottom surface is directionally constrained to restrict vertical movement from thermal expansion, while other boundaries remain unconstrained

2.3 Multi-Field Coupling Theory The thermal response under microwave irradiation represents a coupled electromagnetic-thermal-mechanical behavior. The theoretical framework comprises Maxwell' s equations, heat transfer theory, and solid mechanics, with coupling relationships illustrated in

Figure 3

Figure 1: Figure 3

.

Electromagnetic Field Theory: Maxwell' s equations describe fundamental electromagnetic relationships. For this model, they are simplified to the Helmholtz vector equation:

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0})\mathbf{E} = 0$$

where $\mathbf{E}$ is electric field intensity (V/m), μ_r is relative permeability, ϵ_r is relative permittivity, σ is conductivity (S/m), ω is angular frequency (rad/s), k_0 is free-space wavenumber, and $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is vacuum permittivity. By specifying input frequency and power, the electromagnetic field distribution in the cavity and specimen is obtained.

Heat Transfer Theory: Microwave energy conversion to heat couples with the specimen' s heat transfer equation through the thermal balance:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = Q_e$$

where Q_e represents microwave-generated heat source (W/m^3), ρ is density (kg/m^3), C_p is specific heat capacity ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), k is thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$), and T is temperature (K). This yields the temperature distribution.

Solid Mechanics Theory: Temperature changes cause thermal expansion and stress. The temperature-strain relationship is:

$$\varepsilon_T = \alpha(T - T_{ref})$$

where ε_T is thermal strain, α is thermal expansion coefficient, and T_{ref} is reference (zero-strain) temperature. Total strain comprises elastic and thermal components:

$$\varepsilon = \varepsilon_\sigma + \varepsilon_T$$

with stress expressed as $\sigma = \mathbf{D}\varepsilon_\sigma$, where $\mathbf{D}$ is the constitutive tensor. These equations enable stress-strain calculation throughout the domain.

2.4 Boundary Conditions Ideal electric conductor boundaries define waveguide and cavity walls. The rectangular waveguide entrance uses a port boundary condition with propagation constant $\beta = \sqrt{k_0^2 - (\frac{m\pi}{a})^2 - (\frac{n\pi}{b})^2}$, where f_c^{mn} is cutoff frequency for mode numbers m, n, and a, b are waveguide dimensions. Impedance boundaries are applied to inner walls.

Convective heat exchange between specimen surface and air causes heat loss:

$$-\mathbf{n} \cdot \mathbf{q} = h(T_s - T_{air})$$

where $h = 20\ \mathrm{W/(m^2 \cdot K)}$ is the convection coefficient and $T_{air} = 25$°C. The specimen bottom contacting the cavity is thermally insulated. For solid mechanics, the bottom surface has directional constraints ($u_z = 0$ mm) while other boundaries are free.

2.5 Mesh Quality Assessment The model mesh must satisfy $L_{max} < \lambda/5$, where λ is wavelength. The cavity maximum element size is 24 mm, specimen maximum size is 5 mm. The final mesh contains 23,463 elements with average quality of 0.664, exceeding the required threshold of 0.15 and ensuring accurate simulation results.

3. Model Validation

Before numerical analysis, model accuracy was validated using thermocouple surface temperature measurements. Two heating protocols were compared: 2 kW for 600 s and 3 kW for 300 s. Experimental and simulated temperature evolutions show consistent trends, though simulated values are typically higher due to idealized assumptions reducing heat losses. Root-mean-square error (RMSE) between experimental and simulated data is calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_{si} - T_{mi})^2}$$

where T_{si} and T_{mi} are simulated and measured temperatures, respectively. RMSE values for mortar and basalt are 16.7°C and 20.7°C at 2 kW, and 13.1°C and 19.7°C at 3 kW, all below the 25.2°C reference threshold, confirming high model reliability.

4. Results and Analysis

4.1 Electric Field Distribution Microwave heating effectiveness depends strongly on electric field distribution. In the empty cavity, electromagnetic waves reflect and refract, creating regions of high and low field intensity. Metal wall interference and waveguide position affect field patterns. When the specimen is inserted, the field redistributes—intensity decreases overall while high-field and low-field positions shift, primarily due to microwave energy absorption by the specimen.

Internal monitoring reveals peak electric field intensity at the basalt center and mortar-basalt interface [FIGURE:6c]. The small specimen size allows wave penetration and internal convergence, producing higher field strength in basalt that increases with input power. Dielectric property differences between materials cause significant field attenuation across the interface, creating substantial field intensity gradients that influence heating rates.

Frequency fluctuations affect microwave absorption efficiency. The absorption rate varies significantly across 2.40–2.50 GHz, reaching minimum (30.86%) at 2.46 GHz and maximum (77.96%) at 2.43 GHz. Frequency changes alter wavelength, affecting energy distribution and penetration depth. Simulations across this range show diverse high-field zone patterns: at 2.40 GHz, strong fields concentrate at the specimen center; at 2.48 GHz, fields shift to the lower X-axis region; at 2.50 GHz, fields appear along the Y-axis midsection. This demonstrates that frequency variations significantly impact heating efficiency and internal field distribution.

4.2 Temperature Distribution and Gradient Temperature fields show distinct high-temperature regions [FIGURE:8a]. Large temperature gradients arise due to non-uniform energy absorption, with maxima occurring at the mortar-basalt interface where field intensity is highest. Temperature gradient distributions [FIGURE:8d] reveal that longer irradiation increases both temperature and gradient magnitude, with more pronounced changes in mortar than basalt due to basalt’ s uniform heating characteristics.

Cross-sectional temperature profiles [FIGURE:8c] show basalt temperatures exceeding mortar temperatures because basalt’ s superior dielectric properties enable greater microwave absorption. The interfacial transition zone, having higher porosity and water-cement ratio, absorbs energy more rapidly when exposed to microwave radiation, creating larger temperature gradients that facilitate interfacial separation.

4.3 Stress and Strain Distribution Temperature gradients induce non-uniform thermal expansion, generating thermal stresses. The first principal stress evolution [FIGURE:9a] shows tensile stresses concentrated at the mortar-basalt interface and basalt exterior, while compressive stresses appear in basalt interior regions. With measured tensile strengths of 7.4 MPa for basalt and 4.65 MPa for mortar, the interface reaches mortar’ s ultimate tensile strength first at 3 kW, 100 s. As heating continues, the tensile zone expands from the interface outward through the mortar, while compressive regions remain relatively stable.

Stress variations along a monitoring line [FIGURE:9b] show maximum tensile stress at the interface, with basalt interior experiencing compression. Due to different thermal expansion coefficients, basalt and mortar expand at different rates under the same temperature, creating interfacial tensile stresses. When these exceed interfacial strength, separation occurs. However, excessive heating time may damage the aggregate itself, as basalt tensile stresses also increase and can reach its strength limit.

Strain distributions [FIGURE:9c] show larger strains in high-temperature basalt regions, with interface strains resulting from combined high stress and temperature effects. The constrained deformation at mortar and basalt edges limits expansion, intensifying internal stresses.

5. Discussion of Multi-Field Coupling and Separation Mechanism

Microwaves generated by magnetrons propagate through waveguides into the resonant cavity, forming standing waves through repeated reflection. In untreated specimens, no cracks appear. When irradiated, electromagnetic waves penetrate and converge within the specimen due to its smaller size relative to penetration depth. Basalt, as a dielectric material, converts microwave energy to heat through dielectric loss, raising specimen temperature.

Dielectric constant differences between mortar and basalt create varying microwave absorption capacities, leading to significant field attenuation at the interface. This produces maximum temperature gradients at the mortar-basalt interface. When the maximum principal stress exceeds mortar’ s tensile strength (4.65 MPa), cracks initiate at the interface and propagate outward. At 3 kW, 100 s, the interface reaches mortar’ s strength limit; by 200 s, cracks extend throughout the mortar region; at 300 s, mortar detaches from basalt. Optimal separation occurs at 200–300 s, removing external mortar while preserving internal aggregate integrity. Excessive duration (400 s) causes basalt damage as both materials reach their strength limits.

6. Conclusions

This study develops a multi-physics coupled mortar-aggregate model validated against experimental temperature data. Key findings include:

1. **Electromagnetic Field:** The cavity exhibits coexisting high and low electric field regions. Specimen insertion redistributes the field, reducing cavity intensity while creating peaks at the mortar-basalt interface and basalt center. Frequency fluctuations significantly affect microwave absorption, with maximum absorption (77.96%) at 2.43 GHz and minimum (30.86%) at 2.46 GHz. Increasing frequency shifts strong field zones from the specimen interior toward the surface.
2. **Temperature Field:** Maximum temperature gradients occur at the mortar-basalt interface, with basalt temperatures exceeding mortar temperatures due to superior dielectric properties. Longer irradiation

increases both temperature and gradient magnitude, with more significant gradient changes in mortar than basalt.

3. **Stress Field:** Maximum tensile stresses appear at the interface, with the tensile zone expanding from the interface to the specimen exterior over time. The interface first reaches mortar’ s ultimate tensile strength, initiating cracking. Compressive stresses dominate in basalt interior regions.
4. **Separation Mechanism:** Optimal irradiation time of 200–300 s at 3 kW effectively removes surface mortar while preventing aggregate damage. The combined effects of electromagnetic field concentration, temperature gradient, and thermal stress at the interface drive the separation process.

References

[1] KIM H, HANIF A, USMAN M, et al. Influence of waste incorporation on early strength concrete properties and cement replacement: environmental impact on hydration and durability attributes[J]. Journal of cleaner production, 2018, 172: 3056-3065.

[2] DIMITRIOU G, SAVVA P, PETROU M F. Enhancing mechanical and durability properties of recycled aggregate concrete[J]. Construction and building materials, 2018, 158: 228-235.

[3] GRABIEC A M, KLAMA J, ZAWAL D. Modification of recycled concrete aggregate by calcium carbonate biodeposition[J]. Construction and building materials, 2012, 34: 145-150.

[4] LIU J, LI Y F, LIU S H. Experimental study on pyrolysis characteristics of tobacco based on microwave heating[J]. Applied thermal engineering, 2016, 106: 473-479.

[5] LAW C L, CHANG S K. Modelling microwave heating of discrete samples and kernels[J]. Applied thermal engineering, 2016, 98: 702-726.

[6] GAO J W, CHENG S T, LI F. Effects of heating methods on mechanical properties of granite[J]. Chinese journal of applied mechanics, 2024, 41(3): 567-574.

[7] SHAO Z S, WEN W, LIU Y. Research progress and engineering applications of microwave heating of rock and concrete[J]. Engineering mechanics, 2020, 37(5): 140-155.

[8] TEIMOORI Z, COOPER C D. Multiphysics study of microwave irradiation effects on a breakage system[J]. International journal of rock mechanics and mining sciences, 2021, 140: 104586.

[9] CHOI W C. Using microwave heating to completely recycle concrete[J]. Journal of environmental protection, 2014, 5(7): 583-596.

[10] ZHANG H L, SHAO Z S, LIU Y. Analysis of splitting tensile properties of concrete under microwave and conventional heating conditions[J]. Engineering mechanics, 2024, 41(5): 134-145.

[11] WEI W, SHAO Z S, LIU Y. Workability and mechanical properties of microwave heating for recovering high-quality aggregate from concrete[J]. Construction and building materials, 2021, 276: 122237.

[12] CHEN Y X, SHAO Z S, LIU Y. Experimental study on heat-induced potential of mortar-aggregate under microwave irradiation[J]. Journal of materials in civil engineering, 2021, 33(7): 04021153.

[13] EVERAERT M, STEIN B, MICHAUX F. Microwave radiation as a pretreatment for standard and innovative fragmentation techniques in concrete recycling[J]. Materials, 2019, 12(3): 324.

[14] LIPPIATT N C, BOURGEOIS F. Investigation of microwave-assisted concrete recycling using single-particle testing[J]. Minerals engineering, 2012, 31: 71-81.

[15] HAQUE K E. Microwave energy for mineral treatment processes—a brief review[J]. International journal of mineral processing, 1999, 57(1): 1-24.

[16] LIANG W, SHAO Z S, LIU Y. Microwave-assisted breakage of basalt: a viewpoint for analyzing thermal and mechanical behavior of rock[J]. Energy, 2023, 273: 127225.

[17] ZHU Y K. Three-dimensional numerical simulation of thermal response of shale subjected to microwave heating[J]. Chemical engineering journal, 2021, 410: 124586.

[18] LIU H, SHAO Z S, LIU Y. Numerical analysis of mechanical properties and multi-field effects at concrete mortar-aggregate interface under industrial microwave irradiation[J]. Journal of materials science and engineering, 2023, 41(1): 30-38.

[19] FIA P R, AMORIM J F. Heating biomass in microwave household oven—numerical study[J]. Energy, 2021, 218: 119472.

[20] MOHD S M, MOKHTAR M, SALMAN M. Simulation studies on microwave-assisted pyrolysis of biomass for bioenergy production with special attention to waveguide number and location[J]. Energy, 2020, 190: 116474.

[21] HUANG Y H, SHAO Z S, LIU Y. Microwave field coupled electromagnetic irradiation, heat transfer model and numerical simulation of coal[J]. Processing technology, 2018, 177: 237-245.

[22] AKBARNEZHAD A, ZHANG M H. Microwave-assisted beneficiation of recycled concrete aggregates[J]. Construction and building materials, 2011, 25(8): 3469-3479.

Figure 1

Figure 2: Figure 1

Figure 2

Figure 3: Figure 2

[23] PITTS M. Thermal properties of Cobourg limestone[D]. Kingston: Queen’ s University, 2014.

[24] MOUNANGA P, KHELIDJ A, BASTIAN G. Experimental study and modelling approaches of thermal conductivity evolution of cement paste incorporating hydrating[J]. Advances in cement research, 2004, 16(3): 95-103.

[25] TANG H. Thermal conductivity of sedimentary rocks in Sichuan Basin, Southwest China[J]. Energy exploration and exploitation, 2019, 37(2): 691-720.

[26] HASSANI F P, NEKOOVAGHT M, GHARIB N. The influence of microwave irradiation on rocks for microwave-assisted underground excavation[J]. Journal of mechanics in geotechnical engineering, 2016, 8(1): 1-15.

[27] ZEIML M, LACKNER R, PESAVENTO F. Thermo-hydro-chemical couplings considered for safety assessment of shallow tunnels subjected to fire load[J]. Tunnelling and underground space technology, 2008, 23(2): 199-213.

[28] HONG T. Three-dimensional simulation of microwave heating with varying parameters[J]. Applied thermal engineering, 2016, 93: 1145-1154.

[29] CHEN W, WARNING A, DATTA A K. Susceptors in microwave cavity heating: modeling and experimentation[J]. Journal of food engineering, 2017, 195: 191-205.

[30] PITCHAI K, BIRLA S L. Modeling microwave heating of frozen mashed potato: electromagnetic frequency spectrum[J]. Journal of food engineering, 2016, 173: 124-131.

[31] XIAO Y. Study on mechanism of strength weakening of concrete subjected to microwaves for microwave-assisted concrete recycling[J]. International journal of heat and mass transfer, 2023, 213: 124353.

[32] BRU K, TOUZÉ S, BOURGEOIS F. Assessment of microwave-assisted recycling process for recovery of high-quality aggregates from concrete waste[J]. International journal of mineral processing, 2014, 126: 90-98.

Figures

Figure 4

Figure 4: Figure 4