Damage Classification in Hollow Cement Mortar Specimens Using Machine Learning Algorithms

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Abstract

This study presents a data-driven framework for damage classification in hollow cement mortar specimens using ultrasonic pulse velocity (UPV) testing and machine learning techniques. Specimens with varying cement contents (10%–30%) were prepared under controlled laboratory conditions, and artificial internal cavities were introduced to simulate damage. Ultrasonic signals were recorded and processed to extract 22 features, including wave velocity, travel time, statistical descriptors, and wavelet-based energy parameters derived from Discrete Wavelet Transform (DWT) and Wavelet Packet Transform (WPT). Three supervised classifiers—K-Nearest Neighbors (KNN), Random Forest (RF), and Naïve Bayes (NB)—were implemented. The Naïve Bayes model achieved the highest performance, with an accuracy of 99.00 ± 3.16% and recall of 97.50 ± 7.91%. The results demonstrate that combining ultrasonic testing with machine learning enables accurate and automated damage detection in cement-based materials.

1. Introduction

Cement mortar and concrete are widely used in civil infrastructure due to their strength and durability. However, internal defects such as cracks and voids may develop over time because of environmental exposure and mechanical loading [1]. Early detection of such damage is essential to prevent structural failure and reduce maintenance costs. Testing approaches are generally classified as destructive or non-destructive[2]. While destructive methods provide accurate mechanical properties, they are impractical for in-service structures. Consequently, non-destructive testing (NDT) techniques have become central to structural health monitoring [3]. Among NDT methods, ultrasonic pulse velocity testing is extensively applied to evaluate material homogeneity and detect internal flaws [4]. Ultrasonic wave propagation is influenced by porosity, density, and internal discontinuities [2]. Although ultrasonic testing is effective, signal interpretation becomes challenging due to material heterogeneity and varying mix compositions. Machine learning techniques provide a robust solution for analyzing complex ultrasonic datasets. Previous studies have shown that integrating ultrasonic testing with wavelet-based signal processing enhances damage detection capability [5]. However, comparative assessment of classical supervised algorithms for hollow cement mortar specimens with varying cement content remains limited. This study addresses this gap by developing an integrated ultrasonic–machine learning framework for reliable damage classification.

2. Methodology

Specimen Preparation

Five groups of hollow cement mortar specimens with cement contents of 10%, 15%, 20%, 25%, and 30% were fabricated. Artificial cylindrical cavities (1 cm diameter) were introduced at the center of selected specimens to simulate internal voids [1]. This setup enabled direct comparison between healthy and damaged states.

Ultrasonic Testing

Ultrasonic measurements were conducted using a Pundit Lab device in accordance with ASTM C597. A pair of 54 kHz transducers was applied in direct transmission mode. Ultrasonic pulse velocity (UPV) and wave travel time were recorded, as these parameters are sensitive to internal discontinuities and porosity variations [4].

Signal Processing and Classification

Given the non-stationary nature of ultrasonic signals, Discrete Wavelet Transform (DWT) and Wavelet Packet Transform (WPT) were used for time–frequency decomposition [6]. Twenty-two features—including velocity, travel time, statistical descriptors, and wavelet-based energy parameters—were extracted for classification.

Three supervised algorithms were evaluated: K-Nearest Neighbors (KNN) [7], Random Forest (RF) [8], and Naïve Bayes (NB) [9]. Cross-validation was applied to ensure robustness, and performance was assessed using accuracy, precision, recall, and classification error [8].

3. Results and Discussion

Results showed that increasing cement content led to higher ultrasonic velocity due to reduced porosity and improved material density. Damaged specimens exhibited lower UPV and longer travel times compared to healthy samples, consistent with previous findings [2].

Wavelet-based energy features improved class separability by capturing frequency-dependent changes caused by internal cavities. Among the evaluated models, Naïve Bayes achieved the best overall performance (Accuracy: 99.00 ± 3.16%), followed by Random Forest and KNN. The superior performance of Naïve Bayes can be attributed to the relatively low correlation among extracted features, which aligns with its independence assumption [9].

Table. The classification results obtained from each of these machine learning algorithms.

Algorithm	Accuracy	Error	Recall	Precision	True0	True1	
KNN	92.00 ± 7.89	8.00 ± 7.89	83.75 ± 16.72	89.28 ± 18.85	6	78	Pred1
					14	2	Pred0
Naïve Bayse	99.00 ± 3.16	1.00 ± 7.89	97.50 ± 7.91	99.44 ± 1.76	1	80	Pred1
					19	0	Pred0
					6	80	Pred1

RF (Accuracy)	94.00 ± 8.43	5.00 ± 7.07	87.50 ± 17.68	92.33 ± 18.57	14	0	Pred0
RF (Gain ratio)	93.00 ± 8.23	6.00 ± 9.66	85.00 ± 24.15	82.00 ± 28.98	7	80	Pred1
					13	0	Pred0
RF (Inf gain)	90.00 ± 9.43	8.00 ± 9.19	83.75 ± 21.08	82.65 ± 24.67	7	77	Pred1
					13	3	Pred0
RF (gini index)	96.00 ± 5.16	5.00 ± 7.07	87.50 ± 17.68	92.33 ± 18.57	4	80	Pred1
					16	0	Pred0

These results confirm that integrating ultrasonic testing with machine learning significantly enhances automated damage detection compared to conventional threshold-based interpretation.

4. Conclusion

This study developed an ultrasonic–machine learning framework for damage classification in hollow cement mortar specimens. The findings indicate that:

- Internal cavities reduce ultrasonic pulse velocity.
- Higher cement content increases wave velocity due to reduced porosity.
- Wavelet-based features effectively capture damage-related variations.
- Naïve Bayes achieved the highest classification accuracy (99%).

The proposed methodology provides a reliable and automated approach for structural health monitoring of cement-based materials and can be extended to real-scale infrastructure systems in future research.

5. References

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