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A clustering-enhanced explainable approach involving convolutional neural networks for predicting the compressive strength of lightweight aggregate concrete

Violeta Migallón, Héctor Penadés, José Penadés
Department of Computer Science and Artificial Intelligence, University of Alicante, Spain
Universitat d'Alacant
Universidad de Alicante

INTRODUCTION & AIM

Lightweight aggregate concrete (LWAC) is a practical alternative to conventional concrete in civil engineering, offering advantages such as reduced density, enhanced insulation properties, and improved seismic performance. However, segregation during compaction remains a limitation, potentially leading to non-uniform material distribution and decreased compressive strength (CS). To address this, fresh-state behavior must be carefully controlled, and non-destructive evaluation techniques are essential. Among these, ultrasonic pulse velocity (UPV) stands out as a simple and effective method for detecting segregation, discontinuities, and internal variations in LWAC [1].

OBJECTIVES:

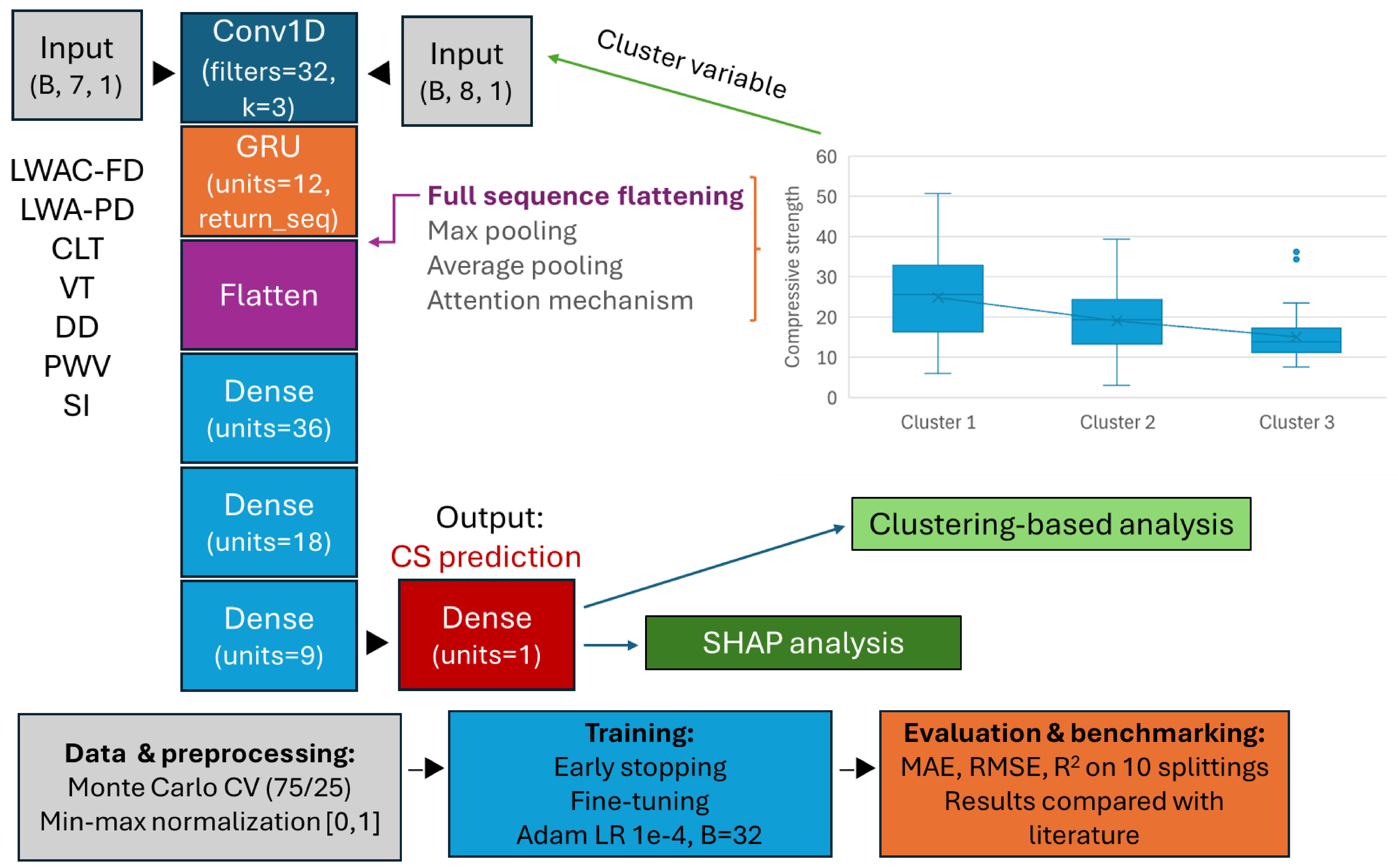
- To develop an interpretable deep learning model to predict the CS of LWAC from UPV and mix-related parameters.
- To integrate explainability methods that show which factors influence predictions.
- To apply unsupervised analysis to reveal hidden patterns in LWAC behavior.

METHOD

Dataset description:

- **Dataset:** 640 core segments from 160 LWAC specimens.
- **Experimental input variables:** LWAC fixed density (LWAC-FD), LWA particle density (LWA-PD), concrete laying time (CLT), vibration time (VT), experimental dry density (DD), local P-wave velocity (PWV), segregation index derived from P-wave velocity per core segment relative to the specimen mean (SI).
- **Key observations (from correlations with CS):**
  - LWA-PD (ρ = 0.708) and DD (ρ = 0.649) → strongest positive predictors of CS.
  - Other relevant correlations: LWAC-FD with DD (ρ = 0.646) and PWV (ρ = 0.520).

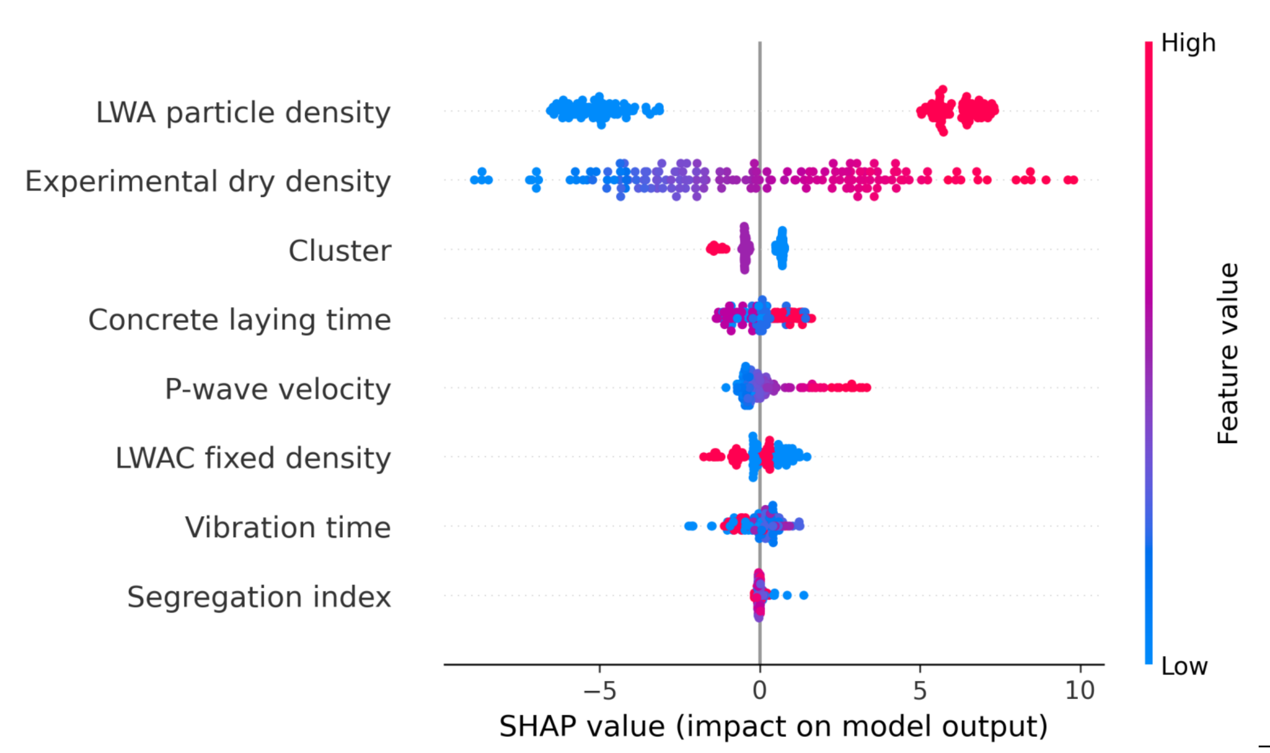
Model architecture design:

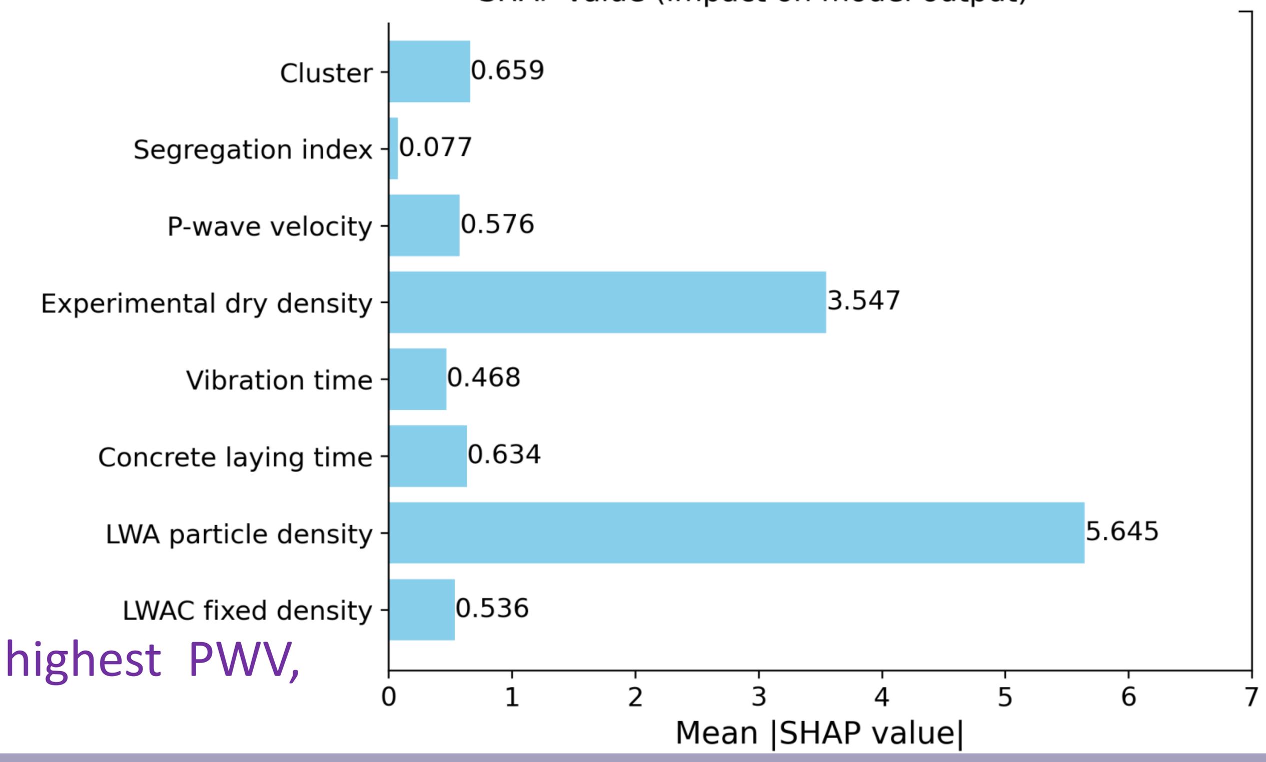


RESULTS & DISCUSSION

Comparison of average test metrics with established results in the literature [2]:

Model	R^2	RMSE	MAE
MLP	0.8045	3.9328	2.9960
RF	0.8135	3.8434	2.9809
SVR	0.8124	3.8543	2.9944
GBR	0.8182	3.7959	2.9209
XGBoost	0.8196	3.7812	2.9020
WAE	0.8220	3.7562	2.8755
Our	**0.8349**	**3.6329**	**2.8213**





Factors influencing CS prediction:

LWA-PD → Strongest predictor ↑ (higher values = higher CS prediction).

DD → Second most important ↑ (higher values = higher CS prediction).

CLUSTER → Third most important:

1 → Increases CS prediction ↑ (best mixes: higher CS, DD and LWA-FD → denser structure).

2 → Slightly decreases CS prediction ↓ (intermediate group).

3 → Decreases CS prediction ↓↓ (weakest mixes: lowest CS and LWA-PD, highest PWV, slightly higher SI).

CONCLUSION

The proposed model outperforms traditional machine learning and ensemble methods, while clustering reveals latent patterns, demonstrating the potential of interpretable deep learning for non-destructive LWAC assessment.

FUTURE WORK

Combine tabular LWAC variables and cluster information with imaging data to improve predictive performance and uncover patterns in concrete cores.

REFERENCES

[1] A. J. Tenza-Abril, Y. Villacampa, A. M. Solak, F. Baeza-Brotons, Prediction and sensitivity analysis of compressive strength in segregated lightweight concrete based on artificial neural network using ultrasonic pulse velocity, Constr. Build. Mater. 189 (2018) 1173-1183.
[2] V. Migallón, H. Penadés, J. Penadés, A. J. Tenza-Abril, A machine learning approach to prediction of the compressive strength of segregated lightweight aggregate concretes using ultrasonic pulse velocity, Appl. Sci. 13 (3) (2023) 1953.