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Key predictors of lightweight aggregate concrete compressive strength by machine learning from density parameters and ultrasonic pulse velocity testing

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INTRODUCTION & AIM

Non-destructive evaluation techniques are increasingly recognised as effective alternatives to destructive testing for estimating the compressive strength of lightweight aggregate concrete (LWAC). Among these, ultrasonic pulse velocity (UPV) is a well-established and widely employed method, characterised by its rapidity, non-invasiveness, and relative simplicity of implementation.

UPV method:

A non-destructive technique to evaluate concrete quality:

- An acoustic wave is transmitted through the material, and the travel time over a known distance is measured.
- Low velocity → cracks, voids, or porosity.
- High velocity → denser and more homogeneous concrete.
- It is fast, reliable, and suitable for both field and lab applications.
- It enables early detection of internal defects before they compromise structural performance.

OBJECTIVES

- ❑ To evaluate machine learning (ML) models using UPV data to predict LWAC strength.
- ❑ To analyse the influence of P-wave velocity and segregation index (SI) on model accuracy.
- ❑ To compare the performance of various machine learning models for strength prediction.

METHOD

Experimental Dataset and Variables:

- **Dataset:** 640 core segments from 160 cylindrical specimens of LWAC.
- **Mixtures:** Four designs combining two target densities (1,700 and 1,900 kg/m³) and two LWA types (482 and 1,019 kg/m³).
- **Mix design:** Defined using the Fanjul method [1].
- **Segregation:** Induced by varying vibration time during compaction.
- **Segregation Index (SI):** Ratio of the P-wave velocity measured in a single core segment to the average P-wave velocity of the corresponding specimen [2].
- **Variables:**

Variables	Min	Max
LWAC fixed density (kg/m³)	1,700	1,900
LWA particle density (kg/m³)	482	1,019
Concrete laying time (min)	15	90
Vibration time (s)	0	80
Experimental dry density (kg/m³)	1,070	2,487
P-wave velocity (m/s)	3,044	5,254
Segregation index	0.845	1.136
Compressive strength (MPa)	2.99	50.72

- **Target variable:** Compressive strength measured using a 200 kN machine at a loading rate of 0.25 MPa/s.

Machine Learning Models and Training Process:

- **Methods:** Several ML models were evaluated, including Support Vector Regression (SVR), Random Forest (RF), Gradient Boosting (GBR), XGBoost, LightGBM, Gaussian Process Regression (GPR), and Hybrid Ensemble Techniques (HETs) [3].
- **Training setup:** The dataset was randomly split into training (75%) and testing (25%) subsets, using 10 different partitions.
- **Evaluation metrics**: R^2, RMSE, and MAE.

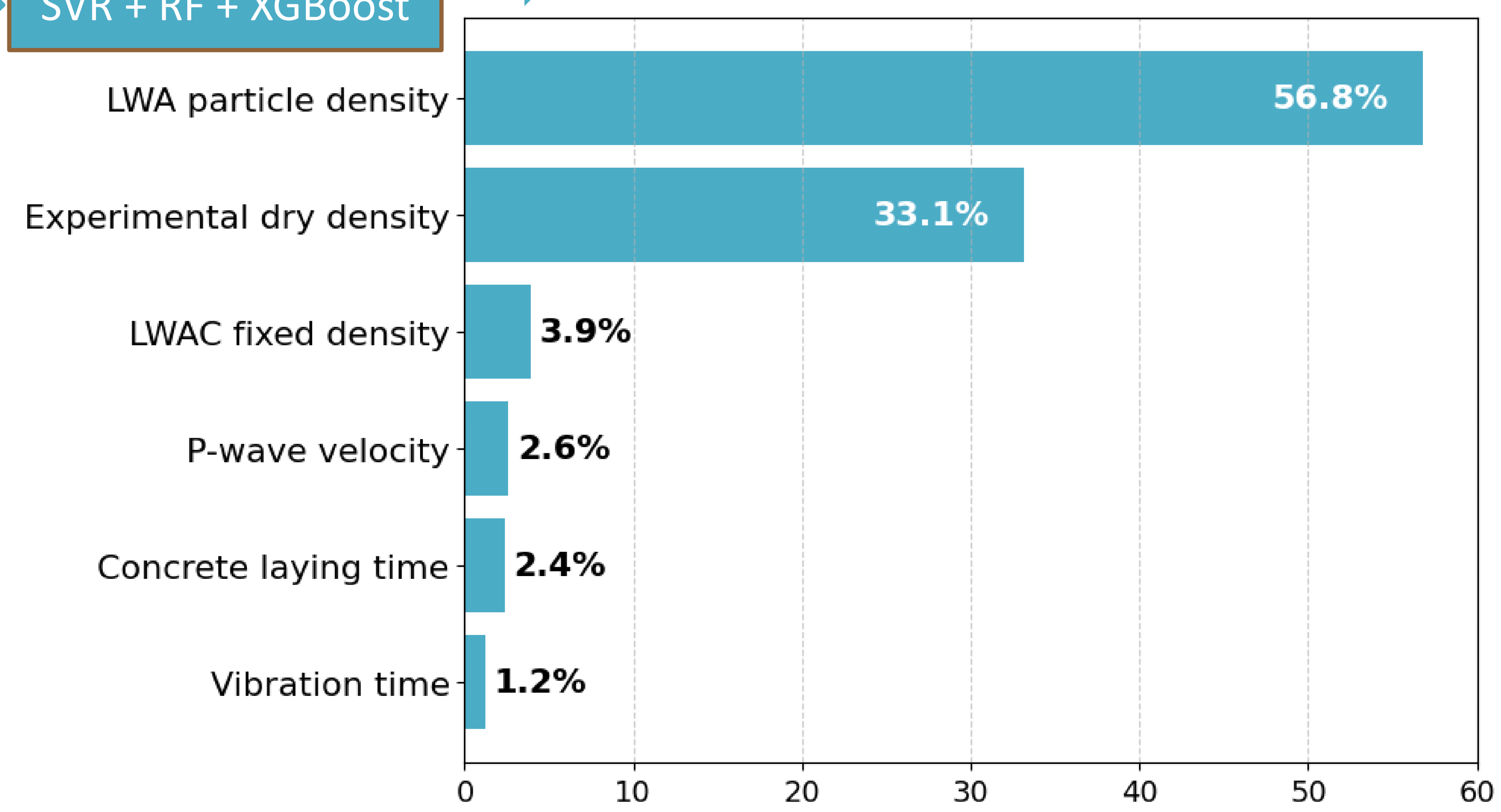
RESULTS & DISCUSSION

Best techniques: Average values of test results.

Model	R^2	R^2 (Without SI)	RMSE	RMSE (Without SI)	MAE	MAE (Without SI)
SVR	0.8200	0.8236	3.7890	3.7669	2.9522	2.9241
RF	0.8210	0.8224	3.7806	3.7652	2.9381	2.9154
GBR	0.8279	0.8291	3.7079	3.6943	2.8962	2.8775
XGBoost	0.8274	0.8267	3.7131	3.7206	2.8927	2.8979
LightGBM	0.8205	0.8238	3.7856	3.7502	2.9727	2.9317
GPR	0.8172	0.8160	3.8208	3.8329	2.9698	2.9768
HET	0.8271	**0.8320**	3.7109	**3.6575**	2.8777	**2.8361**

Weighted Ensemble
SVR + RF + XGBoost

Permutation importance (%) - HET



- P-wave velocity measured by UPV testing is a reliable non-destructive indicator of compressive strength in LWAC.
- Excluding SI slightly improved performance in most models, probably due to its narrow range (0.845–1.136) and redundant information with other variables.

CONCLUSIONS AND FUTURE WORK

- HET techniques using UPV data yielded R^2 = 0.832, RMSE = 3.6575, and MAE = 2.8361 for LWAC strength estimation.
- Future work will focus on implementing advanced deep learning approaches, supported by explainable AI techniques to achieve more accurate and interpretable predictions of LWAC strength.

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