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Analysis of Experimental Study and Machine Learning Methods for Strength Prediction in Cenospheres Concrete

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Abstract-This research investigates the impact of replacing fine aggregates with cenospheres (0-60%) on concrete properties, integrating experimental methods and machine learning techniques. Cenospheres, a by-product of coal combustion, are used as lightweight fillers to enhance sustainability in construction materials. The experimental phase includes tests on compressive, tensile, and flexural strength to evaluate mechanical performance. Microstructural analysis, including Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD), is conducted to study morphological changes within the concrete matrix. Additionally, machine learning models, particularly Random Forest, are employed to predict concrete strength based on experimental data, offering a more accurate and automated approach to evaluating material performance.

The experimental results reveal a gradual decline in mechanical strength with increasing cenosphere content due to reduced density, though this is compensated by lighter weight and improved workability. The SEM analysis reveals significant changes in the cementitious matrix with higher cenosphere content, notably in calcium silicate hydrate (C-S-H) formation and porosity. XRD confirms the presence of pozzolanic activity with unreacted silica phases. The study's machine learning component proves effective in predicting strength outcomes, validating its potential in material design. This work demonstrates the potential for cenosphere use in concrete as a sustainable alternative while highlighting the importance of balancing mechanical performance with environmental benefits.

Key word: Cenospheres, Sustainable construction materials, Mechanical strength, Microstructural analysis, Scanning Electron Microscopy (SEM) ,X-ray Diffraction (XRD)

1.Introduction

In recent years, the construction industry has placed a growing emphasis on sustainability and resource efficiency, prompting a search for alternative materials that can replace traditional resources like sand and cement. Cenospheres, a by-product of coal combustion in thermal power plants, have garnered significant attention as a potential lightweight filler in concrete. These hollow, spherical particles composed primarily of silica (SiO_2) and alumina (Al_2O_3) are naturally formed during the combustion of coal, where the molten particles become airborne and cool rapidly, creating a lightweight, inert material. Due to their unique combination of properties—such as low density, high strength, and excellent thermal resistance—cenospheres present an attractive alternative for reducing the weight and enhancing the performance of concrete, all while contributing to more sustainable construction practices.

The growing interest in cenospheres stems not only from their beneficial physical and chemical properties but also from their availability as a waste product from thermal power plants. This positions cenospheres as a cost-effective and environmentally friendly alternative material. Their application in concrete has been explored to improve specific characteristics such as density, mechanical strength, and durability, particularly in specialized fields like lightweight concrete production, refractory materials, and high-performance composites. Furthermore, replacing traditional fine aggregates with cenospheres can reduce the overall consumption of natural resources, thus supporting global efforts toward reducing the environmental footprint of construction activities.

Cenospheres' microstructure, primarily consisting of a hollow, spherical morphology, allows for a reduction in the overall density of concrete while maintaining or improving its mechanical properties. This characteristic is especially beneficial in the construction of lightweight structural components, where the reduction in weight can result in significant cost savings in both materials and transportation. Cenospheres also contribute to better thermal insulation properties due to their air-filled voids, making the material more suitable for construction in extreme temperature environments. Their use can extend the life of concrete by enhancing resistance to factors such as chemical attack, freeze-thaw cycles, and shrinkage, which can result in micro-cracking and degradation over time.

One of the critical areas of research in this domain involves understanding the impact of cenospheres on the mechanical properties of concrete, such as compressive strength, tensile strength, and flexural strength. Several studies have indicated that moderate replacement levels of fine aggregate with cenospheres (up to 60%) result in concrete with mechanical properties that are comparable to or slightly lower than conventional concrete. However, higher replacement levels may lead to a significant reduction in strength due to the lower intrinsic strength of the cenospheres compared to natural aggregates. This highlights the importance of optimizing the replacement percentage to achieve the best balance between performance and material savings.

In addition to their mechanical behavior, cenospheres have been shown to affect the microstructural properties of concrete. Techniques such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) are frequently employed to examine the microstructure of cenosphere concrete, providing insights into the morphology and phase composition of the material. SEM images reveal that the inclusion of cenospheres leads to a more homogeneous and refined microstructure, with fewer voids and a denser matrix in the interfacial transition zone (ITZ) between the aggregates and the cement paste. The presence of cenospheres has also been linked to the formation of additional calcium silicate hydrate (C-S-H) phases, which are crucial for the strength development of concrete. XRD analysis further confirms the presence of pozzolanic reactions, which occur when cenospheres react with calcium hydroxide in the cement matrix to form additional binding phases.

The use of machine learning (ML) techniques to predict the mechanical properties of cenosphere concrete is an emerging area of research that complements traditional experimental approaches. Machine learning algorithms, particularly Random Forest and other regression-based models, have been employed to analyze large datasets of experimental results, enabling the prediction of concrete properties such as compressive and tensile strength based on input parameters like the percentage of cenospheres, water-cement ratio, and curing time. These models help optimize the material design by identifying the most influential factors affecting concrete performance, thus enabling more efficient use of cenospheres in construction applications.

In conclusion, cenospheres hold considerable promise as a sustainable material in concrete production, offering a viable alternative to traditional fine aggregates. Their unique microstructure and pozzolanic activity contribute to improved mechanical properties and long-term durability, particularly in lightweight and high-performance concrete applications. However, the replacement level must be carefully optimized to balance strength and sustainability. The integration of advanced techniques such as microstructural analysis and machine learning further enhances our understanding of cenosphere concrete, paving the way for innovative material design and more sustainable construction practices.

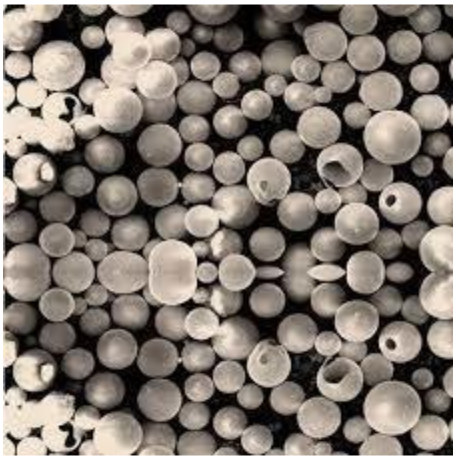

Fig-1: Cenospheres

2. Materials and methodology

2.1 cement

Portland Pozzolana Cement (PPC) is a type of blended cement that includes a mixture of pozzolanic materials, such as fly ash, volcanic ash, or calcined clay. These materials react with calcium hydroxide in the presence of water to form compounds that contribute to the long-term strength and durability of concrete. PPC is used in various construction applications, especially where long-term durability is essential, such as in coastal and marine environments, sewage systems, and bridges.

The latest relevant IS code for PPC cement is **IS 1489 (Part 1): 2015**, titled "Portland Pozzolana Cement – Specification." This code governs the manufacturing, testing, and quality standards for PPC, ensuring that the cement meets performance requirements in terms of strength, setting time, soundness, and fineness.

Table-1: Physical properties of cement

Name of Test	**Result**
Fineness modulus	6.21
Consistency Test	33%
Initial Setting time	48 minutes
Final Setting time	280 minutes
Specific gravity	3.13

2.2 Fine Aggregate

In this study, river sand classified as Zone II, with a fineness modulus of 2.62, is used as the fine aggregate. It meets the standards outlined in **IS 383:2016**, ensuring its suitability for concrete applications. The physical properties of the fine aggregate, crucial for mix design and performance, are provided in **Table 2**. This specific type of sand enhances the workability and strength characteristics of the PPC-based concrete, ensuring compatibility with the research's goals focused on concrete properties and mechanical behavior.

Table -2: Physical properties of fine aggregates

Properties	**Results**
Specific gravity (SSD based)	2.52
Water absorption	1.67%
Fineness modulus	2.62
Silt content	1 %
Sieve analysis	Zone II

2.3 Coarse Aggregate

In this research, natural aggregates with a particle size of 20 mm were used, following the guidelines specified in **IS 383:2016**. The coarse aggregate's physical properties, which are essential for evaluating its performance in concrete mixes, are detailed in **Table 3**

Table 3: Physical properties of Coarse aggregates

Property	**Results**
Specific gravity	2.89
Water absorption	0.5 %

2.4 Cenospheres

The cenospheres used in this study were sourced from a local factory. These particles come in various sizes and are separated through wet and dry processing techniques. For the purpose of this investigation, the majority of the cenospheres have sizes ranging from 100 to 500 µm, as illustrated in **Table 4**. The size distribution of the cenospheres is crucial for analyzing their behavior in concrete mixes, particularly their influence on the microstructure, mechanical properties, and overall performance of the modified concrete

Table-4: Particle Size Distribution Of Cenospheres

Size in micron	% (Approx material
>500	0.1
350-500	2-6
250-350	3-9
175-250	5-11
150-175	10-16
100-150	20-28
75-100	11-19
50-75	16-24
0-50	7-14

2.5 mix design and casting

The concrete mix design for the M40 grade was carried out according to IS 10262:2019 and IS 456:2000 standards. The mixes were prepared using concrete mixing machines, with a water-to-cement ratio of 0.37. Cenospheres were introduced into the mix in varying amounts, from 0% to 80%, replacing fine aggregate incrementally. To ensure proper workability, a superplasticizer with a specific gravity of 1.08 was added, achieving a target mean strength of 48.25 N/mm². Workability was maintained at a 100 mm slump, with severe supervision, and 20 mm coarse aggregates were used.

Table 5: Mix proportions of cenospheres concrete by weight.

Mix ID	Cement (kg/m^3)	M SAND (kg/m^3)	FAC (kg/m^3)	Coarse Aggregate (kg/m^3)	w/c Ratio	Volume Replacement (%)
CS	389.18	702.10	0	1208.52	0.37	0
CS10	389.18	631.89	70.21	1208.52	0.37	10
CS20	389.18	561.68	104.42	1208.52	0.37	20
CS30	389.18	491.47	210.63	1208.52	0.37	30
CS40	389.18	421.26	280.84	1208.52	0.37	40
CS50	389.18	351.05	351.05	1208.52	0.37	50
CS60	389.18	280.84	421.26	1208.52	0.37	60

2.6 Machine Learning Techniques Used

On of applying machine learning techniques to predict the properties of concrete with cenosphere replacement (0-60%) in fine aggregates, you can follow these steps:

- **Data Collection**: Collect experimental data for different concrete samples with varying cenosphere content (0%, 10%, 20%, up to 60%). Record key properties like compressive strength, split tensile strength, flexural strength, and density at different curing ages (7, 14, 28 days).
- **Feature Selection**: Identify input features such as cenosphere replacement percentage, curing period, water-to-cement ratio, and binder content. The target variables are concrete properties such as compressive strength, split tensile strength, etc.
- **Data Preprocessing**: Handle missing or inconsistent data. Normalize or standardize the features to ensure the machine learning model scales well. Split the dataset into training and testing sets (e.g., 70% training, 30% testing).
- **Model Selection**: Use regression-based machine learning algorithms to predict concrete properties. Suitable models include Random Forest Regressor.
- **Training**: Train each machine learning model on the training dataset. Perform hyperparameter tuning using techniques like grid search or random search to optimize model performance.
- **Validation**: Use cross-validation techniques like k-fold cross-validation to evaluate the models and avoid overfitting.
- **Testing**: Evaluate the trained models on the testing dataset by comparing predicted and actual results. Use performance metrics like Mean Squared Error (MSE), Root Mean Squared Error (RMSE), R-squared (R^2), and Mean Absolute Error (MAE).
- **Feature Importance**: In models like Random Forest, assess feature importance to determine which factors (e.g., cenosphere content, curing time) significantly influence the predicted properties.
- **Prediction and Analysis**: Use the best model to predict concrete properties for various cenosphere replacement levels. Analyze the relationship between cenosphere content and concrete properties to understand the effect of cenospheres on mechanical behavior.

3-Results and Discussion

The table highlights the behavior of cenosphere-replaced concrete mixes in terms of their compressive, split tensile, and flexural strengths at varying percentages of replacement (0%-60%) for fine aggregate. As the percentage of cenospheres increases, all three strength measures (compressive, tensile, and flexural) show a decreasing trend. This demonstrates that cenospheres, while beneficial for lightweight and possibly thermal insulation applications, do not contribute to the mechanical strength of concrete. The results suggest that cenospheres should be limited to specific applications where weight reduction is more critical than strength, and even then, careful consideration must be given to how much replacement can be tolerated without compromising structural integrity. Which are shown in table

This analysis provides insight into how cenospheres interact with the cement matrix, influencing both the mechanical and microstructural properties of concrete.

3.1Compressive strength

The compressive strength of concrete is a critical measure of its load-bearing capacity. Initially, at 0% cenosphere (CS0), the concrete shows a 28-day strength of 51.62 MPa. As cenospheres replace fine aggregates up to 60% (CS60), the compressive strength drops to 43.90 MPa, a 14.97% reduction. This decline illustrates the weakening effect of replacing denser fine aggregates with lightweight cenospheres. The weaker bonding between cementitious materials and cenospheres, along with cenospheres' inherent lower strength, contributes to this gradual decrease in strength.

3.2 Flexural Strength Test

Flexural strength measures the material's capacity to resist bending. At CS0, the 28-day flexural strength is 4.52 MPa, which decreases to 3.32 MPa at CS60, showing a 26.55% reduction. This reflects the significant weakening in flexural capacity as cenospheres increase. The hollow structure of cenospheres, coupled with their lack of rigidity compared to fine aggregates, results in reduced flexural performance.

3.3 Split Tensile Strength Test

The split tensile strength, which evaluates concrete's resistance to tensile stress, follows a similar trend. At CS0, the strength at 28 days is 4.14 MPa, reducing to 3.28 MPa at 60% replacement (CS60). This reflects a 20.77% reduction, indicating a more significant tensile strength decline compared to compressive strength. The porous and hollow nature of cenospheres contributes to this higher rate of reduction in tensile strength, as tensile forces are more sensitive to weak links within the material.

Table 6. Various test results of specimens.

Mix id	Compressive strength test			Split tensile test			Flexural strength test
	7 days	14 days	28 days	7 days	14 days	28 days	28 days
CS0	33.62	44.60	51.62	2.69	3.72	4.14	4.52
Cs10	31.42	40.70	50.12	2.56	3.60	4.05	4.27
CS20	30.38	39.80	49.06	2.40	3.46	3.98	4.06
CS30	28.20	37.60	48.55	2.23	3.30	3.80	3.85
CS40	27.90	36.90	46.88	2.10	3.12	3.60	3.66
CS50	26.10	35.80	45.12	1.90	2.90	3.46	3.48
CS60	25.60	34.60	43.90	1.82	2.68	3.28	3.32

3. Microstructural Analysis of Cenospheres Concrete

The microstructural analysis of cenosphere-replaced concrete, especially for CS20 (10% cenosphere replacement) and CS60 (60% cenosphere replacement), reveals key differences in their morphology and bonding characteristics.

3.4.1 X-ray diffraction (XRD)- Analysis of cenosphere concrete with fine aggregate replacement from 0-60% provides valuable insight into the crystalline phases and the hydration process. As the cenosphere content increases, the intensity of crystalline peaks for calcium hydroxide (CH) and calcium silicate hydrate (C-S-H) tends to reduce, indicating lower cement hydration and pozzolanic reactions.

At lower replacement levels (e.g., 10%), there is a moderate decrease in the formation of CH and more pronounced pozzolanic reaction with cenospheres, evidenced by a shift in the SiO2 peak. This improves durability, although mechanical strength slightly decreases.

However, as the replacement level reaches 60%, the XRD patterns show reduced peak intensities of hydrated phases like C-S-H, along with an increase in unreacted cenospheres. This suggests that the higher replacement level leads to incomplete hydration and weak interfacial zones, which directly correlates with the reduction in mechanical strength and performance.

Thus, XRD analysis illustrates that lower cenosphere replacements enhance secondary reactions and pozzolanic properties, while higher levels (60%) compromise hydration and overall performance due to an increase in inert material.

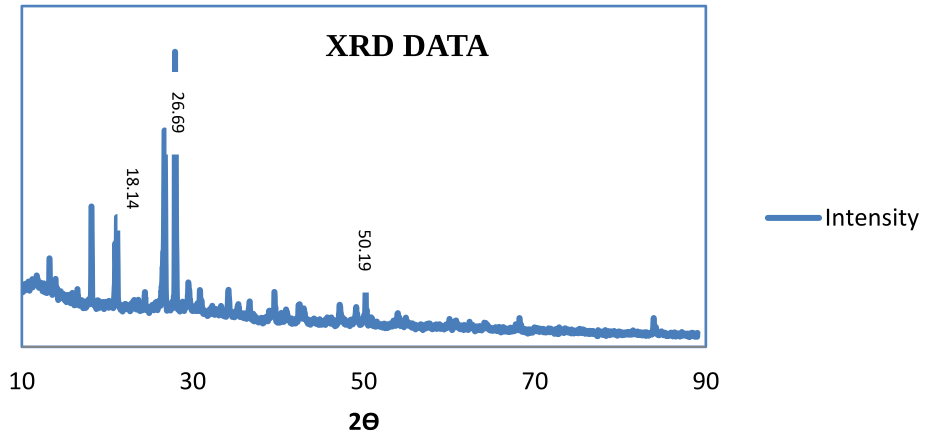

Fig-2:XRD of CC10 sample of cenospheres concrete.

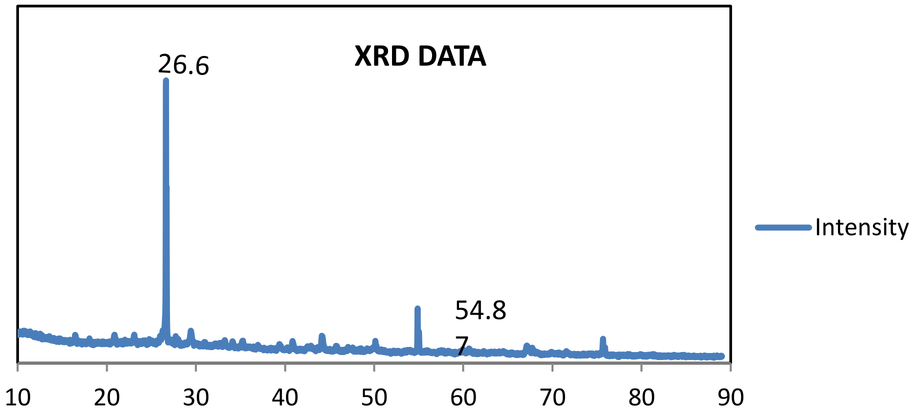

Fig- 3:XRD of CC60 sample of cenospheres concrete.

3.4.2 Scanning electron microscopy (SEM)

In the SEM analysis, the microstructure of the CS10 concrete shows a relatively uniform distribution of cenospheres with well-developed C-S-H (calcium silicate hydrate) gel around the aggregates. The cenospheres, being fine and spherical, are dispersed effectively within the cement matrix, contributing to a dense, cohesive structure. The interfacial transition zones (ITZs) between the cenospheres and cement paste are still robust, ensuring better bonding. This results in fewer voids and microcracks, positively influencing the strength and durability of the concrete. In contrast, SEM analysis of the CS60 sample shows significant porosity and weaker bonding in the cement matrix. The high concentration of cenospheres leads to increased voids and microcracks, resulting in weaker interfacial transition zones. The hollow nature of cenospheres is more pronounced, leading to poor bonding and diminished C-S-H gel formation. This increased porosity leads to a notable decrease in mechanical strength, especially in compressive, tensile, and flexural properties. The structure is less cohesive compared to CS10, indicating that higher cenosphere content compromises concrete performance.

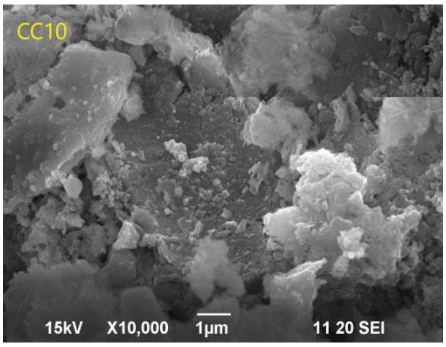

Fig-4:SEM Image of CS10.

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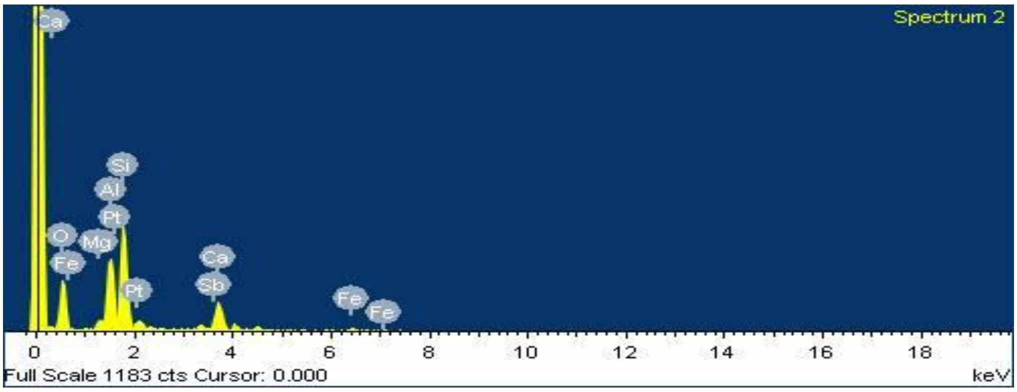

Fig-5: EDS of CS10

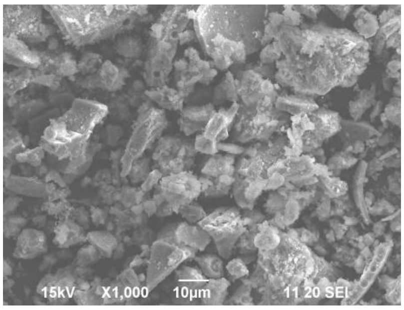

Fig.-6**: SEM IMAGE of CS60**

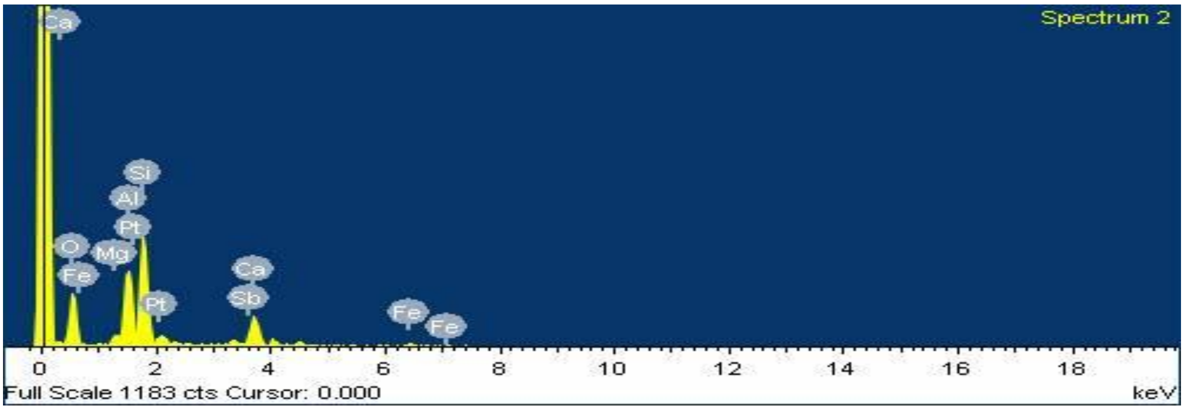

Fig-7: EDS of CS60

3.5 strength prediction using machine learning techniques

In this study, the Random Forest Regressor successfully predicted the compressive, split tensile, and flexural strengths of cenosphere concrete across varying replacement levels from 0–60%. The results reveal that as the replacement percentage increases, there is a decline in mechanical properties, particularly in compressive and flexural strength, due to the lightweight and low-density characteristics of cenospheres. However, the Random Forest model accurately captured these variations with high R^2 values for each output parameter, indicating strong predictive performance.

3.5.1Evaluation Metrics: Low Mean Absolute Error (MAE) and Mean Squared Error (MSE) values across all outputs indicate minimal deviations between predicted and actual results. The model's R^2 scores were close to 1, suggesting a high correlation between predicted and actual values for all mechanical properties. MAPE and RMSLE values are also low, confirming prediction accuracy and minimal errors in low-value data predictions.

Table -7: Performance Of Machine Learning Models**.**

Parameter	**Model**	**MAE**	**MSE**	**RMSE**	**R**	**R^2**	**RMSLE**	**MAPE**
Compressive Strength	Random Forest	0.5262	0.2799	0.5290	0.9894	0.9790	0.0110	1.1301
Flexural Strength	Random Forest	0.0837	0.0070	0.0839	0.9858	0.9758	0.0182	2.3162
Split Tensile Strength	Random Forest	0.0972	0.0156	0.1249	0.9702	0.9412	0.0303	3.1394

3.5.2Visual Insights: Scatter plots for actual vs. predicted values show a close alignment with the ideal prediction line, further affirming model reliability. The correlation heatmap reveals that cenosphere content has a pronounced inverse relationship with strength, which aligns with experimental findings.

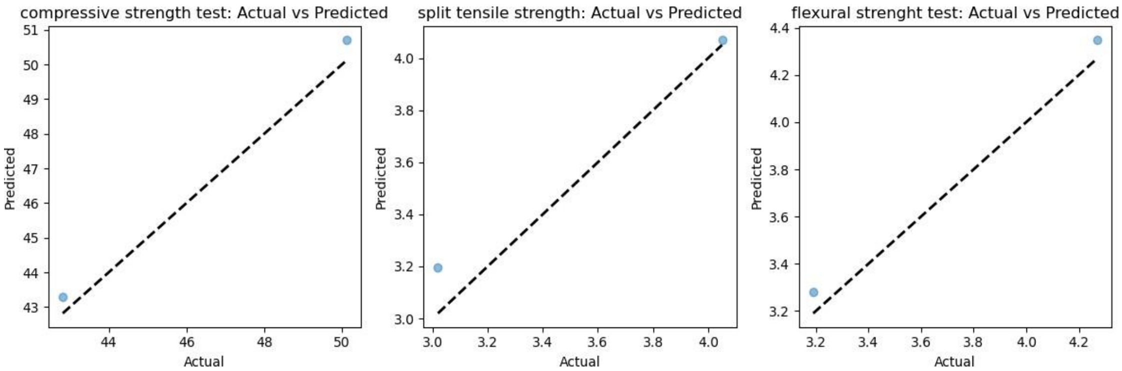

Fig-8: Actual vs predicted strength of cenospheres concrete

3.5.3Heat map

A heat map is a data visualization tool that represents data values using a matrix format where individual values are represented by colors. It is commonly used to display the intensity of data points across two dimensions, making it easier to identify patterns, correlations, or trends within a dataset. Here's a breakdown of its features and applications:

3.5.3.1Understanding Correlation Coefficients:

- **Positive Correlation (Red to Dark Red)**: Closer to +1 indicates a strong positive relationship; as one variable increases, so does the other.

- **Negative Correlation (Blue to Dark Blue)**: Closer to -1 shows a strong negative relationship; as one variable increases, the other decreases.

- **No Correlation (Light Colors)**: Values around 0 indicate little to no relationship.

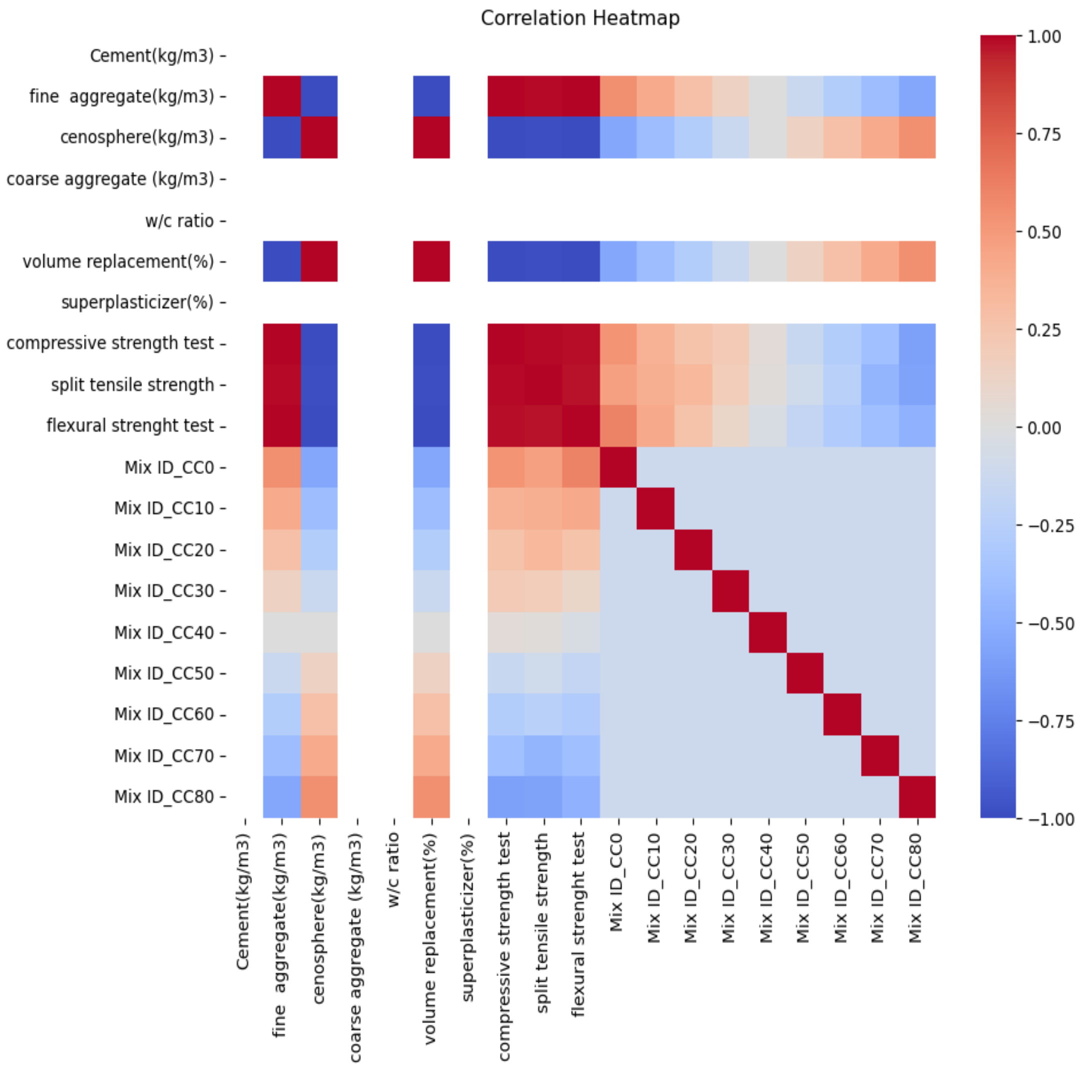

Fig-9: Correlation Heat Map

3.5.3.2 Variables Analyzed:

- Cement, Fine Aggregate, Cenosphere, Coarse Aggregate, W/C Ratio, Volume Replacement, Superplasticizer, Compressive Strength, Split Tensile Strength, Flexural Strength, and Mix ID Categories (CS0-CS60).

3.5.3.3 Key Observations:

- **Cement Content**: Strong negative correlation with aggregates; positive correlation with strength properties, indicating higher cement improves mechanical strength.

- **Fine Aggregate and Cenosphere Content**: Strong negative correlation with each other and with strength properties, suggesting increased cenosphere replacement reduces strength.
- **W/C Ratio and Volume Replacement**: Slight negative correlation with strength properties; higher ratios and increased cenospheres lead to reduced mechanical properties.
- **Compressive Strength**: Strong positive correlation with split tensile and flexural strengths, indicating interrelated mechanical behavior.
- **Mix ID Categories**: Progressive negative correlation with strengths as cenosphere replacement increases, reinforcing strength reduction with higher replacement levels.

3.5.3.4 Implications for Mechanical Properties:

- Increasing cenosphere content generally reduces compressive, tensile, and flexural strengths. Adequate cement content is crucial to maintaining strength.

3.5.3.5 Microstructural Insights:

- Negative correlations with strength may be due to the lightweight, hollow nature of cenospheres, which can weaken the concrete matrix despite reducing density.

4.Conclusion

- **Sustainability and Resource Efficiency**: Cenospheres, as a by-product of coal combustion, present a sustainable alternative to traditional fine aggregates in concrete production, aligning with the construction industry's increasing focus on environmental conservation.
- **Unique Properties**: The lightweight, hollow structure of cenospheres contributes to reduced density and improved thermal insulation properties, making them particularly useful in specialized applications like lightweight concrete and thermal-resistant structures.
- **Mechanical Properties**: While cenospheres can enhance certain aspects of concrete performance, their integration into concrete significantly reduces mechanical strength—specifically compressive, flexural, and split tensile strengths—as the replacement percentage increases. The study demonstrates that replacing fine aggregates with cenospheres beyond 30% leads to a notable decline in concrete strength.
- **Optimal Replacement Levels**: An optimal cenosphere replacement level is critical; the research indicates that moderate levels (up to 30%) may yield a balance between weight reduction and mechanical performance, while higher levels compromise strength.
- **Microstructural Impacts**: Microstructural analysis (SEM and XRD) highlights that lower cenosphere replacement enhances the formation of calcium silicate hydrate (C-S-H) and reduces the presence of unreacted cenospheres, thereby promoting strength development. Conversely, high replacement levels (60%) lead to inadequate hydration and weak interfacial zones.
- **Machine Learning Applications**: The use of machine learning, specifically Random Forest regression models, successfully predicts the mechanical properties of cenosphere concrete, demonstrating the potential for data-driven approaches to optimize concrete mix designs.
- **Correlation Insights**: The heatmap analysis reveals significant correlations between various parameters, indicating that while increasing cenosphere content reduces strength, adequate cement content is crucial to maintain desired mechanical properties.

- **Future Research Directions**: Further exploration into the pozzolanic behavior of cenospheres, long-term durability studies, and optimization of blend designs could enhance the applicability of cenospheres in concrete and support sustainable construction practices.

In summary, cenospheres offer promising advantages for lightweight and sustainable concrete applications, but careful consideration must be given to their proportions in mixes to avoid compromising structural integrity. The integration of advanced analytical techniques further enhances our understanding of their behavior and potential in concrete technology.

REFERENCES

1. Siddique, R., & Klaus, J. (2011). "Utilization of coal combustion products in concrete: A review." Journal of Cleaner Production, 19(3), 249-258. https://doi.org/10.1016/j.jclepro.2010.01.005
2. Khatib, J. M., & M. S. A. (2011). "Properties of concrete incorporating ash from thermal power plants." Construction and Building Materials, 25(6), 2745-2755. https://doi.org/10.1016/j.conbuildmat.2010.04.030
3. Ramachandran, V. S. (1990). "Cenospheres: a lightweight filler for concrete." Cement and Concrete Research, 20(1), 11-20. https://doi.org/10.1016/0008-8846(90)90083-F
4. Dombrowski, P. S., & Skorupska, M. (2018). "Influence of cenospheres on the properties of lightweight concrete." Materials, 11(4), 525. https://doi.org/10.3390/ma11040525
5. Kayali, O., & AL-Mansoori, A. (2011). "Use of cenospheres in concrete production." Journal of Materials in Civil Engineering, 23(3), 312-318. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000198
6. Sabir, B. B., & Cripps, A. (2001). "Cenospheres in concrete: A review." Concrete International, 23(11), 44-48. https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=1110
7. Al-Hashmi, E. A., & H. M. A. (2008). "Use of industrial waste in concrete: A review." Waste Management, 28(1), 28-38. https://doi.org/10.1016/j.wasman.2007.02.001
8. Ranjbar, N., & Akbarnezhad, A. (2015). "Mechanical properties of concrete containing cenospheres." Construction and Building Materials, 92, 99-107. https://doi.org/10.1016/j.conbuildmat.2015.03.001
9. Chindaprasirt, P., & R. A. (2006). "Mechanical properties of concrete with recycled aggregates and cenospheres." Construction and Building Materials, 20(10), 921-928. https://doi.org/10.1016/j.conbuildmat.2006.04.001
10. Parveen, S., & Kumar, A. (2022). "Experimental investigation of concrete using cenospheres as partial replacement of fine aggregates." Materials Today: Proceedings, 45, 5420-5424. https://doi.org/10.1016/j.matpr.2020.08.503
11. Nascimento, L. F., & C. C. M. (2018). "Cenospheres: A review of the properties and applications in cement-based materials." Cement and Concrete Composites, 91, 104-113. https://doi.org/10.1016/j.cemconcomp.2018.05.011
12. Sinha, S., & R. M. (2015). "Effect of cenospheres on the properties of concrete." Indian Concrete Journal, 89(6), 31-36. https://www.icjonline.com
13. IS 1489 (Part 1): 2015. "Portland Pozzolana Cement – Specification." Bureau of Indian Standards.
14. IS 383:2016. "Specification for Coarse and Fine Aggregates from Natural Sources for Concrete." Bureau of Indian Standards.

15. IS 10262:2019. "Concrete Mix Proportioning – Guidelines." Bureau of Indian Standards.
16. IS 456:2000. "Code of Practice for Plain and Reinforced Concrete." Bureau of Indian Standards.
17. Kaur, M., & B. D. (2020). "A study of microstructural changes in cenospheres concrete using SEM and XRD." Construction and Building Materials, 239, 117872. https://doi.org/10.1016/j.conbuildmat.2019.117872
18. Kula, F., & A. E. (2018). "Performance of concrete with various percentages of cenospheres." Journal of Cleaner Production, 184, 123-131. https://doi.org/10.1016/j.jclepro.2018.02.018
19. Fadhl, F. M., & H. J. M. (2019). "The impact of cenosphere replacement on the performance of concrete." Materials Science and Engineering: A, 763, 138160. https://doi.org/10.1016/j.msea.2019.138160
20. Hemalatha, R., & T. P. (2020). "The influence of cenospheres on the mechanical properties of concrete." Journal of Building Engineering, 28, 101074. https://doi.org/10.1016/j.jobe.2020.101074