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Performance Evaluation of Bottom Ash as Aggregate Replacement in Conventional Roller-Compacted Concrete (RCC): An Experimental Study

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Abstract. The escalating demand for construction materials, coupled with the depletion of natural resources such as sand, necessitates environmentally conscious alternatives in concrete production. This study investigates the viability of utilizing bottom ash as an eco-friendly substitute for natural sand in roller compacted concrete (RCC). The focus is on evaluating workability and mechanical properties, examining bottom ash replacements at 0%, 20%, 25%, and 30% for fine aggregate. The research employs a comprehensive methodology, assessing workability and mechanical strength, encompassing compressive, split tensile, and flexural strengths across various concrete formulations. Comparative analyses with conventional concrete provide conclusive insights. Significantly, the study consistently highlights the superiority of RCC specimens featuring a 25% bottom ash replacement, exhibiting the highest strength values. This establishes the 25% replacement ratio as optimal for achieving robust roller-compacted concrete. Despite a slight reduction in workability with increasing bottom ash replacement, it remains within acceptable limits for practical applications. Comparative analyses between bottom ash RCC and conventional RCC underscore the superior mechanical attributes of the former, suggesting its potential as a sustainable alternative in concrete construction. By substituting natural sand with bottom ash, this research addresses environmental concerns related to the depletion of sand reserves. It actively contributes to sustainable practices within the concrete industry, demonstrating the viability of bottom ash as a substitute for natural sand in roller compacted concrete production. In conclusion, the study advocates for environmentally friendly practices and offers a practical solution to mitigate the ecological impact of sand resource depletion in the realm of concrete construction. The findings emphasize that the optimum percentage of bottom ash for compressive strength, split tensile strength, and flexural strength tests is within the range of 0% to 12%.

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1 Introduction

The migration of people from rural to urban areas has led into a significant rise in the number of tall buildings in cities. This trend is particularly prominent in developing countries where infrastructure development is reaching its peak. Concrete plays a vital role in the construction of tall buildings and various infrastructure endeavours, and river sand serves as the main source of fine aggregate, which is an essential component in concrete production. However, the availability of river sand is gradually diminishing from its natural sources. The scarcity of river sand has become a pressing issue due to the importance of environmental preservation and mining restrictions imposed in certain areas [1]. Over the past two decades, it has become evident that there is a decreasing supply of high-quality natural sand. The current alternative method of crushing stones to obtain fine aggregate is undesirable from a sustainable construction standpoint as it causes harm to the environment and creates noise pollution. A more economically and environmentally beneficial approach would be to incorporate industrial waste as an alternative, either partially or entirely for river sand in concrete, while maintaining its desirable qualities. Therefore, the search for a substitute for river sand in concrete has become more critical than ever, considering the current shortage of river sand sources and the rapid pace of infrastructure development [2].

The combustion of 2.9 million tonnes of coal produces approximately 1.2 million metric tonnes of ash. In Malaysia, the annual production of bottom ash amounts to 1.7 tonnes. Since 1988, seven thermal power stations in Malaysia have been using coal as a fuel for combustion. However, the availability of bottom ash dumpsites is decreasing, making the safe and efficient management of this industrial waste increasingly important. While biomass-based power generation is considered a potential alternative to conventional fuels, coal power generation remains a widely regarded and efficient method for producing electricity due to its technological and economic benefits. In terms of energy production, thermal coal occupies a greater proportion when compared to the combustion of oil and gas. The significant production of fly ash (FA) and bottom ash (BA), which are two by-products of coal combustion, poses a critical challenge for thermal power plants. The disposal of BA in ponds presents a risk to human and environmental health due to the potential release of harmful components that can seep into the soil or surface water, causing pollution. BA particles have a rough surface and an angular shape, ranging in size from small pebbles to fine sand (10-0.75 mm). In comparison to fine aggregates, coal BA is lighter and brighter. Around 25% of the total ash generated from combustion is converted into coal BA, while the remaining 75% is in the form of FA. The inclusion of BA in concrete mix design offers a unique component [3]. The use of bottom ash as a construction material has garnered increased attention from researchers due to its low cost and excellent sustainability, making it a suitable substitute for conventional construction materials. Reports indicate that incorporating BA in concrete provides resistance to acid attacks [4].

Coal Bottom Ash (CBA) is a residue from coal combustion in thermal power plants, comprised of dense particles settling at the combustion chamber's base. It constitutes 15–25% of total coal ash production. Integrating CBA into concrete mixes impacts their workability. Studies show that increasing the proportion of oven-dried CBA in concrete leads to decreased slump. Likewise, incorporating 10–30% bottom ash into high-workability concrete mixes results in reduced slump flow and passing ability [1,5]. This slump reduction is attributed to the voids within the oven-dried CBA structure, absorbing mixing water. The ash, abundant in empty pores, absorbs water that would otherwise aid particle movement in the mix. Consequently, the frictional force within the mix increases, leading to a decrease in workability.

Another factor reducing the workability of the mix is the physical characteristics of coal bottom ash, such as its interlocking behavior, irregular shape, and coarse surface texture. Due to its larger surface area compared to sand, incorporating ash particles smaller than 300μm decreases workability. However, some researchers argue that bottom ash can improve mix workability. They discovered that using saturated surface dry bottom ash instead of sand enhances workability. Replacing 30% to 100% of sand with bottom ash can facilitate the concrete mixing process [5].

Literature indicates that using bottom ash as a partial sand substitute impacts the load-bearing capacity of concrete. Several studies have shown that incorporating a small amount of bottom ash into concrete can enhance its strength. For instance, adding 10% coal bottom ash to standard concrete improves its strength. The optimal strength was achieved by using 15% finer-sized bottom ash (passing 600 μm) compared to other proportions [1]. Research indicates that coal bottom ash can be used as a binder, fine aggregate, or coarse aggregate in concrete, depending on its particle size. The most consistent improvements in concrete strength and pore structure are observed when coal bottom ash replaces sand as a fine aggregate [2]. Coal bottom ash has a particle size distribution like river sand and is generally well-graded, but it is lighter and more brittle. Its low specific gravity and porous structure make it prone to degradation under load or compaction. However, coal bottom ash derived from high-sulfur, low-rank coal tends to be denser and less permeable. The properties of coal bottom ash are affected by factors such as the degree of coal pulverization, initial furnace temperature, and furnace type used. Concrete is a complex blend of different elements, including cement, fine aggregate (FA), coarse aggregate (CA), water, and optional admixtures. It has emerged as a preferred choice for construction and infrastructure projects. Being the most widely used construction material globally, concrete is renowned for its resilience and robustness. While concrete exhibits a relatively high compressive strength, its tensile strength is comparatively low. Therefore, it is common practice to reinforce concrete with materials that possess high tensile strength, such as steel.

The development of roller compacted concrete (RCC) was driven by the need for faster and more cost-effective construction of dams. RCC is a type of concrete that is mixed with soil and rockfill components and has zero slump, meaning it is highly stiff when fresh [6]. Roller-compacted concrete (RCC) has become popular in constructing hydraulic structures, road pavements, highways, and other applications due to its cost-effectiveness and rapid production. In the 1970s, RCC pavements began to replace traditional asphalt pavements because of their lower construction costs. RCC differs from conventional concrete in several key aspects: it has a lower water content, includes more mineral additives (such as bottom ash), and involves specific production and construction processes. Aggregates make up about 70-80% of RCC's volume, which allows for better filling of larger voids with fine aggregates. The post-curing behaviour of RCC relies on the precise application, compaction, and management of layers during distribution using bulldozers and compaction with vibrating rollers [7].

2 Methodology

For the experimental study, four different mix design of well graded coal bottom ash as sand replacement in concrete were prepared with the primary objective is to compare RCC performance at various ratios and identify the right mix that yields the best outcomes. Concrete cubes of various sizes were used for the tests, including cubes of 100 mm x 100 mm x 100 mm for compressive strength tests, 200 mm x 100 mm for split tensile tests, and 100 mm x 100 mm x 400 mm for flexural tests. The compressive strength test aimed to determine the maximum load-bearing capacity of the material under compression until failure. The split tensile test involved loading cylindrical specimens with diametral forces to measure the material's tensile strength. Lastly, the flexural test assessed the material's ability to withstand bending stresses. The obtained test results were thoroughly analysed and evaluated to ascertain the optimal mix proportion for RCC. This crucial information can be instrumental in designing RCC for diverse construction applications, such as dams, pavements, and heavy-duty industrial floors. Compressive strength, split tensile strength, and flexural tests are essential for assessing the strength and durability of RCC. These tests aid in determining the optimal mix proportion for RCC, which may vary depending on the specific application of the material.

For acquiring 28th day compressive strength, a control mix, CM (without coal bottom ash), is made. Then, coal bottom ash is used in place of fine aggregate (M sand) at a weight ratio of 20%,25% and 30%. The mixes are given the designations CM, BA20%, BA25% and BA30%, respectively. The qualities of each mix then examined both when it is still fresh and when it has hardened. The designation of concrete mix design in unit weight (kg/m3) are shown in Table 1 and Mix design in weight (kg) in Table 2, respectively. They were mixed with cement, gravel, and water. All mixtures were then tested using the ASTM C143 standard for slump tests, the ASTM C109 test method for compressive strength, and the ASTM C518 standard for thermal conductivity tests.

Table 1. Designation of concrete mix design in unit weight (kg/m^3).

Mix Designation	**OPC Grade (kg/m^3)**	**W/Cement (%)**	**Water (kg/m^3)**	**Fine Aggregate (kg/m^3)**	**Bottom Ash (kg/m^3)**	**Coarse Aggregate (kg/m^3)**
CM	750	0.36	270	975.00	0.00	1575
BA20%	750	0.36	270	780.00	195.00	1575
BA25%	750	0.36	270	731.75	243.75	1575
BA30%	750	0.36	270	682.50	292.50	1575

Table 2. Mix design in weight (kg).

Mix Designation	**OPC Grade (kg)**	**Water (kg)**	**Fine Aggregate (kg)**	**Bottom Ash (kg)**	**Coarse Aggregate (kg)**
CM	22.18	7.98	28.83	0	46.57
BA20%	22.18	7.98	23.06	5.77	46.57
BA25%	22.18	7.98	21.62	7.21	46.57
BA30%	22.18	7.98	20.18	8.65	46.57

3 Results and discussions

3.1 Slump test

The results obtained for the slump test were tabulated in Table 3. The slump test results obtained were as follows: 50mm for the control mixture, 43mm for 20% replacement, 40mm for 25% replacement, and 36mm for 30% replacement. The slump test is commonly utilized to assess the workability of concrete by measuring its consistency and flowability, which provides valuable insights into its ability to be easily placed and compacted. In the present study, the obtained slump values clearly demonstrate the variations in workability that occur because of substituting fine aggregate with bottom ash.

The decrease in slump values as the percentage of bottom ash replacement increases indicates a decline in workability. For instance, with an increase in replacement percentage from 20% to 30%, the slump values decreased from 43mm to 36mm. This decline strongly suggests that the inclusion of bottom ash significantly impacts the flowability and ease of handling of the roller compacted concrete (RCC) mixtures. Multiple factors can be attributed to the reduction in workability. Firstly, disparities in particle shape, size, and texture between fine aggregate and bottom ash can influence the flowability of the mixture. Fine aggregate typically comprises well-defined particles with uniform shapes, while bottom ash particles possess irregular shapes and sizes due to the combustion process in power plants. The irregular shape and larger particle size of bottom ash can contribute to a more congested mixture, thereby diminishing workability. Additionally, the texture of bottom ash might differ from that of fine aggregate. Fine aggregate usually has a smoother texture, whereas bottom ash particles may have a rougher surface. This difference in texture can increase friction between particles and impede the flow of the RCC mixture.

Furthermore, the higher water absorption properties of bottom ash compared to fine aggregate might also contribute to the reduced workability. The greater water absorption of bottom ash can result in a higher water demand in the mixture, affecting its consistency and workability. By comparing the slump values of the control mixture with different replacement percentages, valuable insights can be gained regarding the efficiency of bottom ash as a substitute for fine aggregate. As the proportion of bottom ash increased, there was a consistent decrease in slump values when compared to the control mixture. This consistent decrease indicates a diminishing workability trend associated with the increasing use of bottom ash as a replacement material.

In nutshell, the findings from the slump test analysis demonstrated a clear and significant impact on the workability of roller compacted concrete when fine aggregate is substituted with bottom ash. As the percentage of bottom ash replacement increases, the slump values noticeably decrease, indicating a reduction in the flowability and ease of handling of the concrete. These effects can be attributed to variations in the particle characteristics of bottom ash and fine aggregate, as well as the superior water absorption capabilities of bottom ash. It is crucial to comprehend these effects to optimize the utilization of bottom ash as a replacement material and achieve the desired workability in roller compacted concrete mixtures.

Table 3. Slump value.

Mix Design	Slump value (mm)
CM	50 (± 0.82)

BA20%	43 (± 0.47)
BA25%	40 (± 0.94)
BA30%	36 (± 1.25)

3.2 Compressive strength

The compressive strength of concrete with varying levels of bottom ash replacement was investigated, as presented in Table 4 and Figure 1. The control mixture exhibited strengths of 15.72 MPa at 3 days, 23.27 MPa at 7 days, and 43.47 MPa at 28 days. Increasing the percentage of bottom ash replacement correlated with higher compressive strengths. Concrete with 20% replacement showed strengths of 16.66 MPa at 3 days, 25.63 MPa at 7 days, and 49.19 MPa at 28 days. At 25% replacement, strengths were 27.96 MPa at 3 days, 35.96 MPa at 7 days, and 28 days. A 30% replacement level resulted in strengths of 24.69 MPa at 3 days, 30.83 MPa at 7 days, and 50.59 MPa at 28 days.

The findings suggest that substituting fine aggregate in concrete with bottom ash can lead to an increase in compressive strength. When assessing concrete's performance, it is vital to consider its compressive strength, which measures its ability to resist compression. A higher compressive strength indicates greater resistance to tension. The compressive strength test is of utmost importance in evaluating concrete as it provides insights into its characteristics. Several factors can impact the compressive strength of concrete, such as the type and quantity of aggregate, water-cement ratio, curing conditions, and the presence of additives or replacements. The ratio of water to cement significantly influences compressive strength. A lower water-cement ratio generally results in higher compressive strength by promoting denser and more compact concrete. Curing conditions also play an important role in the development of concrete's compressive strength. Adequate curing ensures that concrete achieves its maximum compressive strength potential.

Table 4. Compressive strength test results (MPa).

Bottom Ash content (%)	**Compressive strength (MPa)**		
	3 days	**7 days**	**28 days**
CM	15.72 (± 0.38)	23.27 (± 0.25)	43.47 (± 0.79)
BA20%	16.66 (± 0.38)	25.63 (± 0.73)	49.19 (± 1.54)
BA25%	27.96 (± 0.11)	35.96 (± 0.48)	55.95 (± 3.21)
BA30%	24.69 (± 1.04)	30.83 (± 1.24)	50.59 (± 1.74)

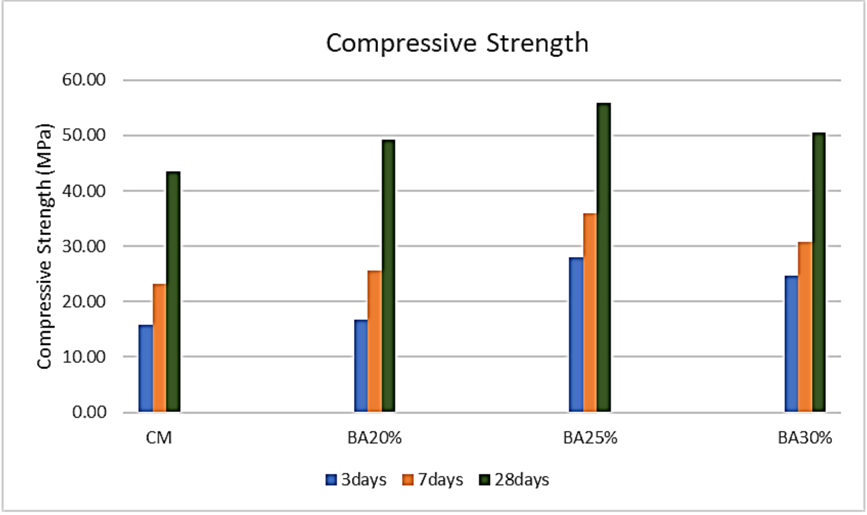

Fig. 1. Compressive strength of samples percentage composition of bottom ash with age.

Model optimization using Design Expert 13 employed Response Surface Methodology (RSM) with Central Composite Design to analyse the compressive strength of concrete. The study investigated various percentages of bottom ash and curing durations across 13 experimental runs. Factor A represented the percentage of bottom ash, Factor B denoted the curing days, and the response variable measured was compressive strength (MPa).

The linear model from the ANOVA is statistically significant for optimizing the studies, as indicated in Table 5. The R-squared (R^2) value of 0.9403 indicates a strong fit of the regression line to the data, corroborated by the predicted vs. actual graph in Figure 2. The adjusted R-squared (Adj. R^2: 0.9284) is a modification of R^2 that considers the number of terms in the model, reflecting improvements beyond chance. While Adj. R^2 can be negative, it is always less than or equal to R^2. R^2 values below 0.75 generally suggest the model does not adequately represent the data. Adequate Precision (Adeq Precision) measures the signal-to-noise ratio, with a ratio greater than 4 being desirable. The Adeq Precision value of 21.008 indicates a sufficient signal. With a significant F-value of 78.76, this model is suitable for navigating the design space effectively.

Table 5. Fit summary results response parameters for Response 1 Compressive strength (MPa).

Response	**Significant model**	**Std. Dev.**	***R^2***	***Adj. R^2***	***Predicted R^2***	***Adeq Precision***	***F-value***
Compressive strength (MPa)	Linear model	3.72	0.9403	0.9284	0.9113	21.008	78.76 (The model is significant.)

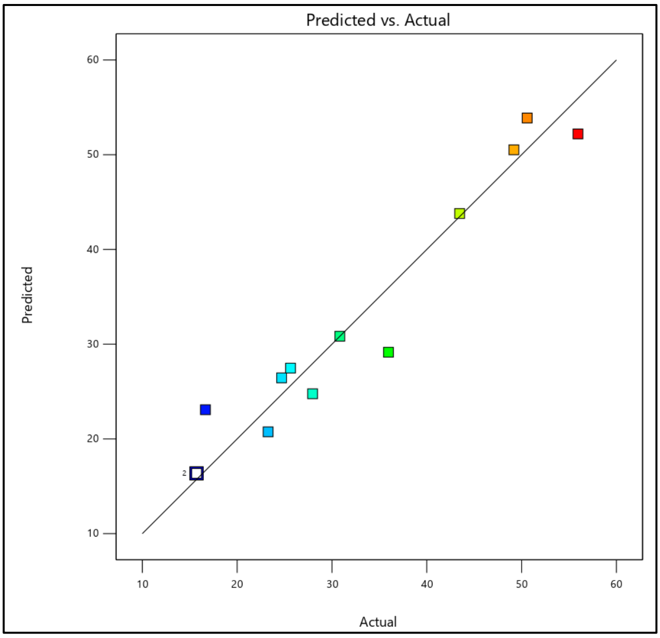

Fig. 2. Compressive strength Predicted vs Actual by Response Surface Methodology.

The β coefficients of determination (R^2) for the quadratic model of compressive strength and model terms are as follows: 35.12 (y-intercept), 5.04 (A – bottom ash percentage), and 13.72 (B – curing days). Both model terms A and B are significant in the linear model. After eliminating non-significant terms, the empirical model expressed in terms of coded factors for the response is presented in the following regression equation (Eq. 1).

$$\text{Compressive strength (MPa)} = 35.12 + 5.04A + 13.72B \tag{1}$$

Figure 3 displays contour plots depicting the relationship between bottom ash percentage (%), curing days (days), and compressive strength (MPa). The compressive strength increases with longer curing durations (from 3 to 28 days), aligning with the typical strength development pattern of concrete. Both the percentage of bottom ash and curing days significantly influence the compressive strength of concrete. For a given curing period, the highest compressive strength was observed at 0 to 12% bottom ash percentage, achieving a strength of 24.79 MPa during curing days 8 to 13. Therefore, a bottom ash percentage of 0 to 12% has been identified as optimal.

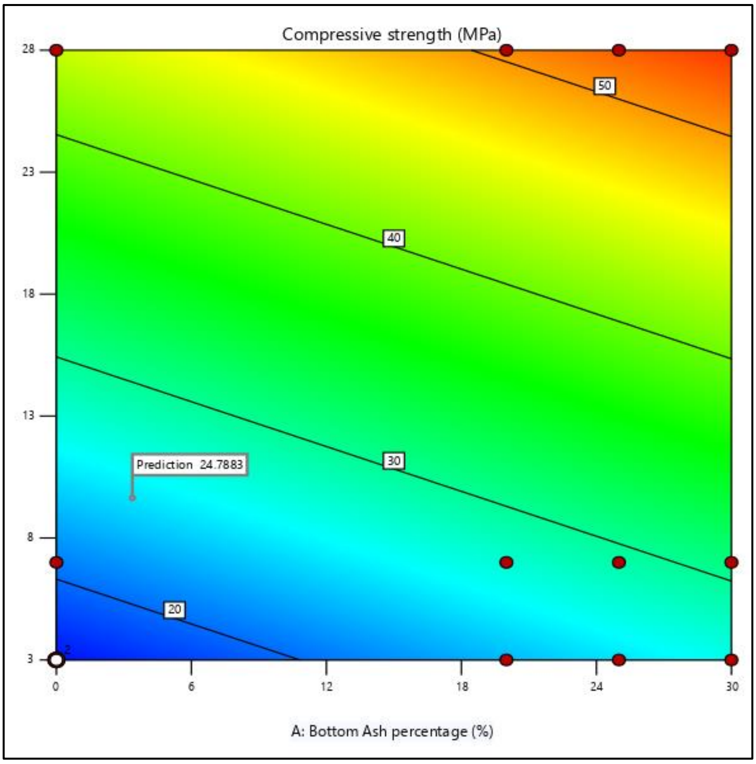

Fig. 3. Compressive strength contour.

A three-dimensional surface plot illustrates the interactions between factors Bottom Ash percentage (%), curing days (day) and compressive strength (MPa) in Figure 4. With a compressive strength of 24.79 MPa and a curing time of 8 to 13 days, the percentage of Bottom Ash is 0 to 12%.

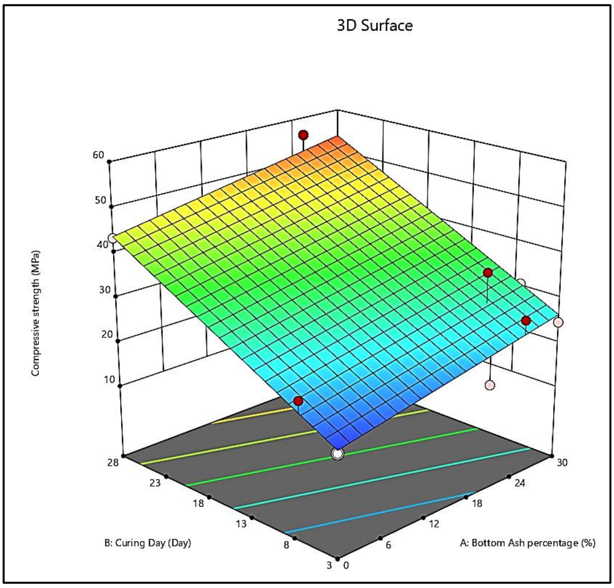

Fig. 4. 3D Surface plots for compressive strength.

The obtained data indicates a positive correlation between the compressive strength of concrete and the percentage of bottom ash replacement. However, determining the optimal replacement percentage depends on the specific application and concrete mixture design. It is crucial to consider other properties of the concrete and take environmental factors into account when contemplating the use of bottom ash. Compressive strength is a critical factor in assessing concrete's ability to withstand compression, influenced by various factors such as the type and amount of aggregate, water-cement ratio, curing conditions, and the presence of additives or replacements. Comprehensive testing and appropriate curing procedures are necessary for achieving optimal compressive strength. Nevertheless, the analysis of both the Response Surface Methodology (RSM) results and the actual laboratory data clearly indicates that the ideal percentage of bottom ash replacement ranges between 0 to 12%.

3.3 Split tensile strength

The investigation into the split tensile strength of concrete with varying levels of bottom ash replacement, as presented in Table 6 and Figure 5, revealed insightful findings. In the control mix, the split tensile strength increased from 2.59 MPa at 3 days to 3.65 MPa at 7 days and 4.77 MPa at 28 days. A mixture with 20% bottom ash replacement showed slightly higher split tensile strength at all ages compared to the control, measuring 2.69 MPa, 3.89 MPa, and 4.92 MPa at 3, 7, and 28 days, respectively. This suggests that bottom ash replacement enhances split tensile strength. At 25% replacement, there was a significant improvement, reaching 3.28 MPa at 3 days, 4.41 MPa at 7 days, and 5.52 MPa at 28 days. However, at 30% replacement, the strength at 3 days was slightly lower than the control but increased to 4.16 MPa at 7 days and 5.42 MPa at 28 days. The results indicate an optimal replacement percentage of 25% for maximizing split tensile strength.

Table 6. Split tensile strength test results (MPa).

Bottom Ash content (%)	**Split tensile strength (MPa)**		
	3 days	**7 days**	**28 days**
CM	2.59 (± 0.05)	3.65 (± 0.06)	4.77 (± 0.02)
BA20%	2.69 (± 0.05)	3.89 (± 0.16)	4.92 (± 0.15)
BA25%	3.28 (± 0.05)	4.41 (± 0.03)	5.52 (± 0.03)
BA30%	2.76 (± 0.05)	4.16 (± 0.13)	5.42 (± 0.07)

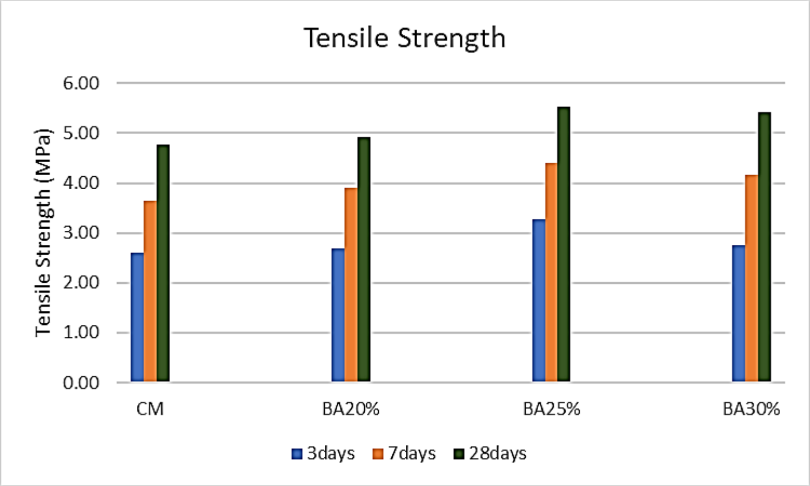

Fig. 5. Split Tensile strength of samples percentage composition of bottom ash with age.

The quadratic model has demonstrated significant relevance for optimization purposes in these studies, as detailed in Table 7. The R-squared (R^2) value of 0.9678 indicates a strong fit of the regression line to the data, a finding reinforced by the results shown in Figure 6 depicting the predicted versus actual graph. The Adjusted R-squared (Adj. R^2: 0.9448) is a modification of R^2 that accounts for the number of explanatory terms in the model, increasing only if additional terms significantly improve model performance. It should be noted that Adj. R^2 can be negative but will always be less than or equal to R^2. R^2 values below 0.75 generally indicate inadequate representation of experimental data. Adequate Precision (Adeq Precision), which measures the signal-to-noise ratio, is crucial for assessing model reliability, with a ratio greater than 4 considered desirable. The Adeq Precision value of 16.8976 in this case indicates an adequate signal. Therefore, this model effectively navigates the design space and is statistically significant, with an F-value of 42.05.

Table 7. Fit summary results response parameters for Response 1 Split Tensile strength (MPa).

Response	**Significant model**	**Std. Dev.**	***R^2***	***Adj. R^2***	***Predicted R^2***	***Adeq Precision***	***F-value***
Compressive strength (MPa)	Quadratic model	0.2511	0.9678	0.9448	0.8417	16.8976	42.05 (The model is significant.)

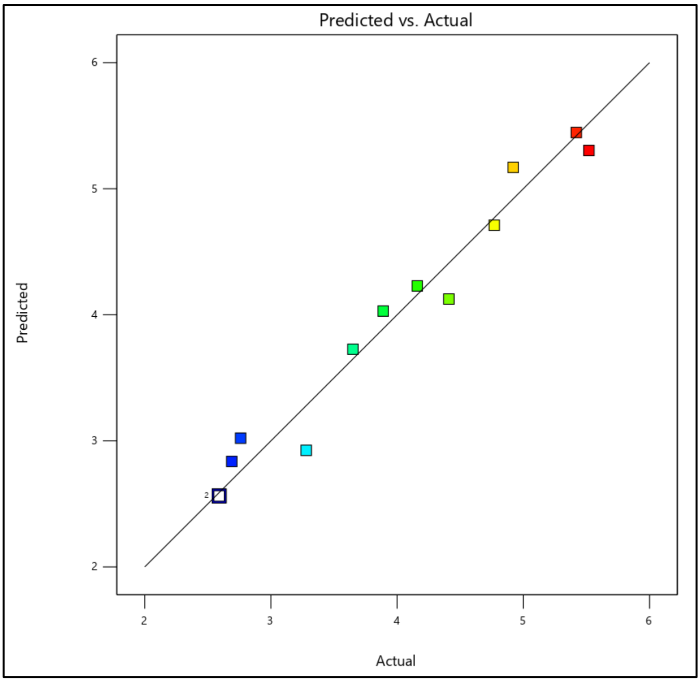

Fig. 6. Split Tensile Strength Predicted vs Actual by Response Surface Methodology.

The β coefficients of determination (R^2) for the Split Tensile Strength Quadratic model and model terms are as follows: 5.42 (y-intercept), 0.2984 (A – Bottom Ash percentage), 1.14 (B – Curing day), 0.0693 (AB), 0.0361 (A^2), and -1.52 (B^2). Model terms A, B, AB, A^2, and B^2 are significant in the quadratic model. Subsequent removal of non-significant terms led to the formulation of the empirical model, expressed in terms of coded factors for the response, as presented in the following regression equation (Eq. 2).

$$\text{Split Tensile Strength (MPa)} = 5.42 + 0.2984A + 1.14B + 0.0693AB + 0.0361A^2 - 1.52B^2 \tag{2}$$

Figure 7 illustrates contour plots depicting the relationship between bottom ash percentage (%), curing days (days), and split tensile strength (MPa). Split tensile strength increases with longer curing periods (from 3 to 28 days), following the typical strength development pattern of concrete. The percentage of bottom ash and curing days significantly influence the split tensile strength of concrete. For a given curing duration, the highest split tensile strength was observed at 0 to 12% bottom ash percentage, achieving a strength of 5.187 MPa during curing days 13 to 18. Therefore, a bottom ash percentage of 0 to 12% has been identified as optimal.

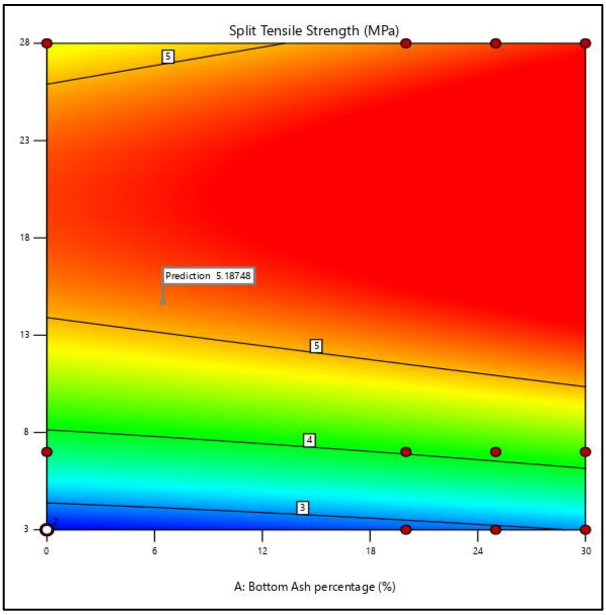

Fig. 7. Split Tensile Strength contour.

Figure 8 depicts a three-dimensional surface plot showcasing the interplay among factors: Bottom Ash percentage (%), curing days (day), and Split Tensile Strength (MPa). At a Split Tensile Strength of 5.187 MPa and a curing duration spanning 13 to 18 days, the corresponding range for the Bottom Ash percentage is 0% to 12%.

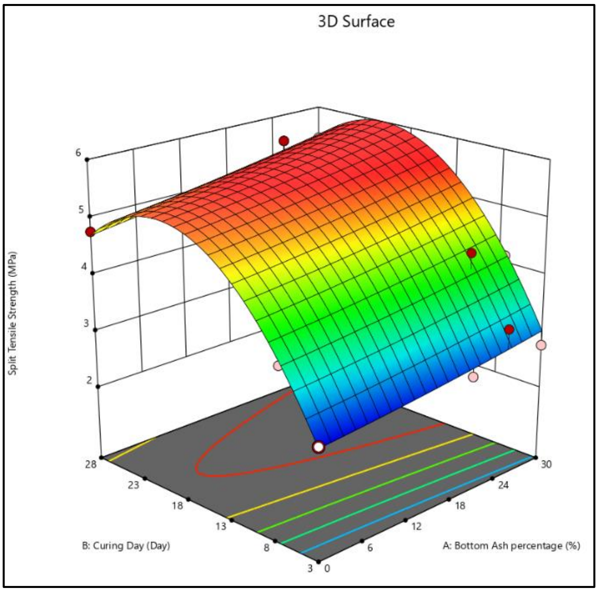

Fig. 8. 3D Surface plots for Split Tensile Strength.

In summary, the incorporation of bottom ash as a fine aggregate substitute proves beneficial for enhancing split tensile strength. The most significant improvement is evident at a replacement rate of 0 to 12%, as indicated by both laboratory data and the Response Surface

Methodology (RSM). This underscores the importance of further research to pinpoint the optimal replacement percentage for maximizing concrete strength.

3.4 Flexural strength

The experimental results of the flexural strength for different levels of fine aggregate replacement with fly ash in the concrete mixture were demonstrated in Table 8 and Figure 9. The findings demonstrated that the flexural strength of the concrete mixture rises with an increase in the percentage of fine aggregate replaced by bottom ash up to a certain threshold, beyond which it starts to decline. Compared to the control blend, the 25% replacement mixture exhibits the highest flexural strength at all ages, while the 30% replacement blend has a lower flexural strength than the 25% replacement mixture, indicating the presence of an optimal replacement percentage that maximizes flexural strength.

Studies examining the influence of replacing fine aggregate with bottom ash on the tensile properties of concrete have yielded varying results. One study indicates that complete replacement of fine aggregate with bottom ash increases compressive strength, while another study suggests that the flexural strength of bottom ash concrete with sand replacement is inferior to that of control concrete specimens across all ages. Nonetheless, both studies agree on the potential use of bottom ash as a fine aggregate substitute in concrete [8] [9] [10]. A review article by Ahady et. All., on the effect of partial replacement of fine aggregate with bottom ash on flexural strength reveals that increasing bottom ash content enhances flexural strength up to a 40% replacement level, beyond which the strength declines [11][12].

Table 8. Flexural strength test results (MPa).

Bottom Ash content (%)	**Flexural strength (MPa)**		
	3 days	**7 days**	**28 days**
CM	2.35 (± 0.09)	3.46 (± 0.18)	4.53 (± 0.14)
BA20%	2.63 (± 0.05)	3.83 (± 0.07)	4.91 (± 0.14)
BA25%	3.00 (± 0.17)	4.62 (± 0.07)	5.68 (± 0.40)
BA30%	2.78 (± 0.07)	4.54 (± 0.08)	5.09 (± 0.13)

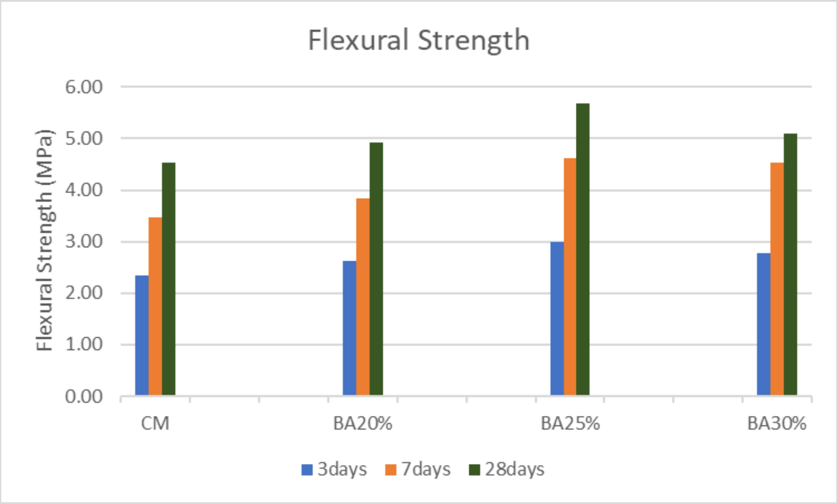

Fig. 9. Flexural strength of samples percentage composition of bottom ash with age.

The quadratic model has proven significant for optimization purposes in these studies, as shown in Table 9. The R-squared (R^2) value of 0.9562 indicates a strong fit of the regression line to the data, supported by the results depicted in Figure 10, which shows the predicted versus actual graph. The Adjusted R-squared (Adj. R^2: 0.9249) adjusts R^2 for the number of terms in the model, increasing only if additional terms significantly enhance the model's performance. It's important to note that Adj. R^2 can be negative but is always less than or equal to R^2. R^2 values below 0.75 generally indicate inadequate representation of experimental data. Adequate Precision (Adeq Precision), which assesses the signal-to-noise ratio, is critical for evaluating model reliability, with a ratio greater than 4 considered desirable. The Adeq Precision value of 14.7956 in this case indicates adequate signal strength. Therefore, this model effectively navigates the design space and holds statistical significance, supported by an F-value of 30.55.

Table 9. Fit summary results response parameters for Response Flexural strength (MPa).

Response	**Significant model**	**Std. Dev.**	***R^2***	***Adj. R^2***	***Predicted R^2***	***Adeq Precision***	***F-value***
Compressive strength (MPa)	Quadratic model	0.3119	0.9562	0.9249	0.8548	14.7956	30.55 (The model is significant.)

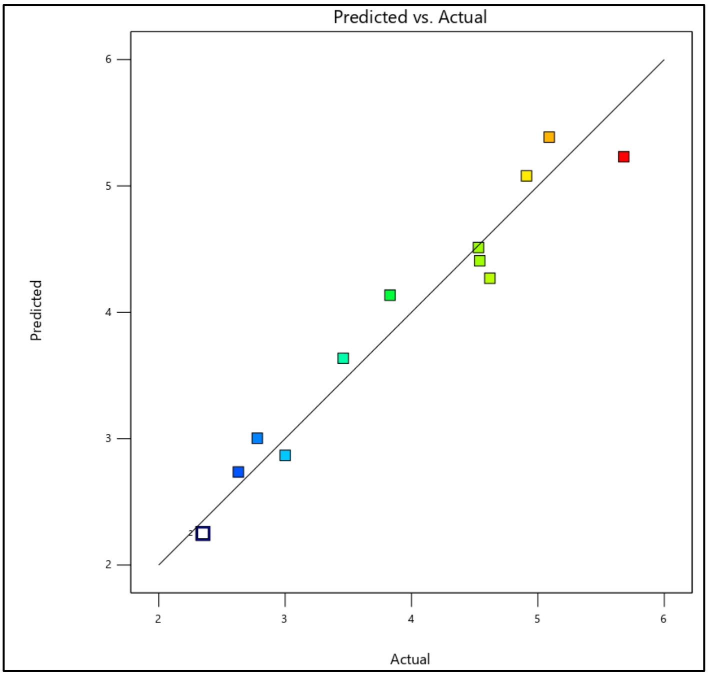

Fig. 10. Flexural strength Predicted vs Actual by Response Surface Methodology.

The β coefficients of determination (R^2) for the Flexural strength Quadratic model and model terms are as follows: 5.67 (y-intercept), 0.4064 (A – Bottom Ash percentage), 1.16 (B – Curing day), 0.0302 (AB), 0.0176 (A^2), and -1.90 (B^2). Model terms A, B, AB, A^2, and B^2 are significant in the quadratic model. Subsequent removal of non-significant terms led to the formulation of the empirical model, expressed in terms of coded factors for the response, as presented in the following regression equation (Eq. 3).

$$\textit{Flexural strength (MPa)} = 5.67 + 0.4065A + 1.16B + 0.0302AB + 0.0176A^2 - 1.90B^2 \quad (3)$$

Figure 11 displays contour plots illustrating the relationship between bottom ash percentage (%), curing days (days), and flexural strength (MPa). Flexural strength increases with longer curing periods (from 3 to 28 days), following the typical strength development pattern of concrete. Both the percentage of bottom ash and curing days significantly influence the flexural strength of concrete. For a given curing duration, the highest flexural strength was observed at 0 to 12% bottom ash percentage, achieving a strength of 5.46 MPa during curing days 13 to 18. Therefore, a bottom ash percentage of 0 to 12% has been identified as optimal.

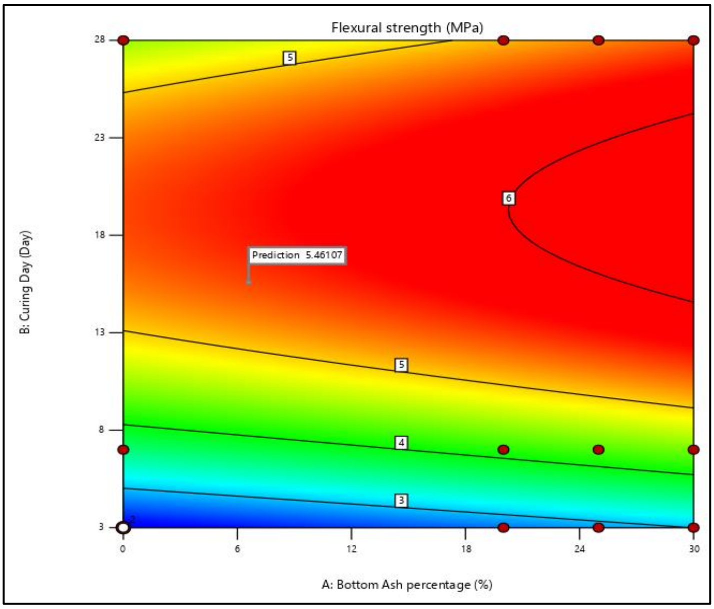

Fig. 11. Flexural strength contour.

Figure 12 depicts a three-dimensional surface plot showcasing the interplay among factors: Bottom Ash percentage (%), curing days (day), and Flexural strength (MPa). At a Flexural strength of 5.46 MPa and a curing duration spanning 13 to 18 days, the corresponding range for the Bottom Ash percentage is 0% to 12%.

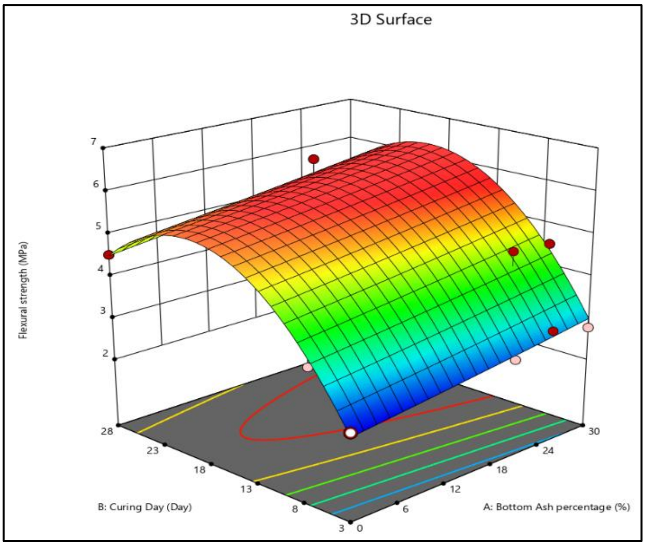

Fig. 12. 3D Surface plots for Flexural strength.

In conclusion, the experimental results suggest that incorporating bottom ash as a partial replacement for fine aggregate in concrete can enhance its flexural strength. The optimal percentage of replacement may vary depending on the specific properties of the bottom ash and other constituents in the concrete mix. Both laboratory testing and Response Surface

Methodology (RSM) indicate that the most effective results typically fall within the range of 0 to 12%. Further research is essential to determine the optimal replacement percentage for different types of bottom ash and various concrete formulations.

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