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Utilization of millet husk ash as a supplementary cementitious material in eco-friendly concrete: RSM modelling and optimization

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ABSTRACT

The environment has been greatly impacted by the increase in cement consumption. However, a huge quantity of energy is consumed and large amount of poisonous gases releases into the atmosphere during the cement production, which harms the environment. In order to decrease not only cement manufacturing but also energy usage and to aid in environmental protection, scientists are attempting to introduce agricultural and industrial waste materials with cementitious characteristics. Therefore, millet husk ash is used as supplementary cementitious material (SCM) in the concrete for producing sustainable environmental. The main purpose of this investigation is to check the workability, compressive strength, splitting tensile strength, flexural strength and drying shrinkage of concrete incorporating 0 %, 5 %, 10 %, 15 % and 20 % of MHA as SCM in concrete. A total of 165 concrete samples was made with mix proportion of 1:1.5:3 and cured at ages of 7, 28, and 90 days. The investigational outcomes displayed that there was an improvement in compressive strength, tensile strength, and flexural strength by 11.39 %, 9.80 %, and 9.39 %, correspondingly, at 10 % of MHA replacement of cement. Also, the water absorption reduced as MHA content increased after 28 days. There was also a reduction in drying shrinkage of concrete as the MHA increased after 28 days. Though, the workability is declined as the proportion of MHA increased in concrete. Moreover, the embodied carbon is declined while the content of PC substituted with MHA rises in concrete. In addition, response prediction models were built and validated using ANOVA at a 95 % significance level. R^2 values for the models varied from 87.47 to 99.59 percent. The study concludes that the accumulation of 10 % MHA in concrete has a favourable effect on the characteristics of the concrete.

1. Introduction

Concrete is the most broadly utilized and fundamental structural material used in all over the world for the development of infrastructure [1]. The necessity and significance of concrete in the construction industry are always growing since its innovation [2]. Lomborg, (2007) stated that the use of concrete is higher than any other artificial material on earth [3,4]. It is an inexpensive, adaptable, and tough material and can be converted into several forms and finishes. Mostly, concrete reduces environmental pollution, and henceforth, concrete structures are designed for long service life [5]. Concrete is an artificial material prepared with ordinary Portland cement and extensively used resources on the Earth planet.

The process of concrete production affect the environment. The most alarming effect is global warming, which is due to CO_2 released during the manufacture of cement [6,7]. From the year 2005, China, for instance, manufactured six billion cubic meters of concrete per year, thus consuming about 40 % world's cement production. The rate of concrete is relatively high owing to the exuberant cost of its main integral, the Portland cement (PC) [1]. The consumption of PC was raised from two million tons in 1880 to about 1.3 billion tons in 1996, and this growth caused the major environmental problem, according to

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Table 1
Oxides composition of binders.

Compound	PC	MHA
SiO_2	20.78	69.40
Al_2O_3	5.11	5.80
Fe_2O_3	3.17	3.36
CaO	60.22	10.50
Na_2O	0.18	1.10
SO_3	2.86	1.85

Fig. 1. Millet Husk before burning.

Fig. 2. MHA after burning.

Malhorta, (2002) [8]. However, the making of one-ton PC discharges around 1 ton of CO_2 in the atmosphere [9,10], and Malhotra presented a report that the manufacturing of cement contributes to being the third biggest carbon-dioxide (CO2) instigator [8]. According to reports, the manufacturing of one ton of cement requires around 1.6 tons of natural assets [11]. PC is a primary integral of concrete, which is not only expensive but also its manufacture generates environmental hazardous [1].

As a result, the cement industry is seeking alternate materials to limit the consumption of cement by undesirable substances. Several investigators carried out experiments utilising SCM in concrete with agricultural/industrial wastes such as wheat straw ash, maize cob ash, rice husk ash, fly ash, groundnut shell ash, wood ash, and so on to boost the strength of structural members while lowering the need of PC [9,12]. Such pozzolanic fillers provide marginal benefits while allowing large quantity of PC replacement to be achieved [13–19]. The proper disposal of these undesired products will improve air quality, reduce solid waste, and ensure the PC and concrete industry's long-term sustainability.

Millet crop is grown widely all over the world as grains for human food. Millet is a significant crop in the semiarid tropics of Asia and Africa [20]. According to the survey, developing countries produce 97 percent of millet [21]. FAO, (2007) presented the report that out of total production of around 28.38 million tons of millet, 40 % is produced in Africa, which was ranked as the second-biggest producer of millet in the World [21,22]. Further, after processing and separating the grains of millet, The husk is either thrown onsite as waste or spread out in an agriculture field and let to compost naturally for months. This composted husk is packed with elements necessary for millet plant growth and serves as an organic fertiliser. Thus, millet husk is used as carbon-based fertilizer by a local farmer who grows this crop. But, on the other hand, this husk, when burnt at a certain temperature, contains cementitious properties similar to that of cement. Moreover, the MHA is attained by incinerated the husk of millet by utilizing controlled burning arrangement method [23]. And this ash can be utilized as a binding ingredient in the making of concrete. The number of experimental researches has been carried out by utilizing MHA as a replacement for PC in mixture. Auta et al., [24] investigated the study on the crushing strength of mix with the inclusion of different proportions of MHA like 0 %-20 %. In this study, concrete specimens were made of 25 MPa and tested for 7, 14, 28, and 35 days. The outcome was exhibited that the crushing strength of mixture blended with 10 % of MHA acquires by 25.56 MPa after 35 days. Uche et al., [1] described that the usage of several proportions of MHA, such as 0 %-50 % as cementitious component in mixture. In this respect, the M15 concrete were made. The result was calculated that the optimum crushing strength was recorded at 5 % of MHA after 28 days.

Furthermore, the primary goal of this experimental investigations is to explored the workability of fresh concrete, water absorption, flexural strength, compressive strength, split tensile strength, and drying shrinkage were analyzed by using response surface methodology (RSM) tool for modeling and optimization. In addition, the embodied carbon and eco-efficiency strength of concrete containing MHA as PC substitutions ingredient in the concrete mixture were analysed.

2. Materials and methods

2.1. Materials

Portland cement (PC) and millet husk ash (MHA) were used as binding material for this research work. The oxides composition of PC and MHA are summarized in Table 1. MHA was achieved by burning the husk of millet under 600 ^{0}C-850 ^{0}C temperature by using the controlled burning method for six hours to convert into ash form. After that ash was left 24 h under the atmosphere to cool down, which was then made to pass through 75 μm BS sieve to ensure uniformity of the particles and to exclude the coarser particles from ash. Figs. 1-3 show the MHA before burning, after burning and after sieving, respectively. After sieving the ash, it was used in this research. The various tests were carried out on cement, and MHA are itemized in Table 2. In this study, hill sand was employed as fine aggregates (FA) that passed through a #4 sieve, while

Fig. 3. MHA after sieve.

Table 2
Aggregates Properties.

Property	FA	CA
Fineness Modulus (FM)	2.21	–
Specific Gravity (SG)	2.64	2.70
Absorption (%)	1.72	1.30
Bulk density (kg/m^3)	1890	1569

Fig. 4. Fine Aggregate.

crushed stone with a size of 20 mm were applied as coarse aggregates (CA) as shown in Figs. 4 and 5. However, the particle grading curves for FA and CA are indicated in Fig. 6, respectively. The properties of aggregates are revealed in Table 2, and Table 3 illustrations the properties of cement and MHA. Moreover, the drinking water was used for carrying out this investigational study.

The micro-scale features of MHA obtained using Scanning Electron Microscopy is revealed in Fig. 7. At low magnification (Fig. 7a), clusters of plate-like crystals were seen, which becomes more visible at high magnification (Fig. 7b). With these images, it may be inferred that MHA contains particles that possess the capability to function as both pore fillers and pozzolans in the matrix.

Fig. 5. Coarse Aggregates.

2.2. *Mixture design*

This experimental investigation was performed concrete blended with 0 %, 5 %, 10 %, 15 % and 20 % of MHA as SCM for measuring the fresh property, mechanical properties and drying shrinkage. A total of 390 concrete specimens were made of 1:1.5:3 mix proportion at 0.54 water-cement ratio and cured at various ages. This mix design was adopted on the five mixtures of concrete, in which one control mix was created using simply PC as the binder and remaining all mixes were cast with addition of 5 %, 10 %, 15 and 20 % MHA to replace PC in concrete. Moreover, the concrete samples like cubes, cylinders and prisms were cast with addition of various content of MHA as a substitution for PC in concrete, and Table 4 displays the precise composition of each mixture examined. The proportion of PC substituted with MHA is shown by the mixture ID in Table 4.

2.3. *Mixing of concrete*

A 0.8 m^3 pan mixer was used to mix all of the concrete materials in the laboratory. All components were dried and mixed in the mixer in the following order: fine aggregates and cement were completely mixed for two minutes to achieve the uniform in colour, and then coarse aggregates were mixed at least three minutes. After that the quantity of MHA was added and mixed for two minutes more to spread properly in the dry mixture and then water was carefully added and mixing continued for several minutes more to achieve a homogeneous mixture. The freshly mixture of concrete was unloaded from the concrete mixer immediately after mixing, and a slump test was performed on fresh mixture within five minutes. After performing slump, the fresh mixture was placed into moulds and then the mixture was compacted into three layers on vibrating table. Furthermore, surface finishing was done to provide an even surface after placing mixture into moulds and all concrete mixtures was left for 24 h in room at room temperature. After 24 h, the moulds was demoulded and immersion in water tank at around 24±2 ^{0}C for the duration of testing day.

2.4. *Testing methods*

The setting time was estimated by using ASTMC187 [25] code for knowing the amount of water desired for the normal consistency of PC paste. The slump test was designed to measure the workability of fresh

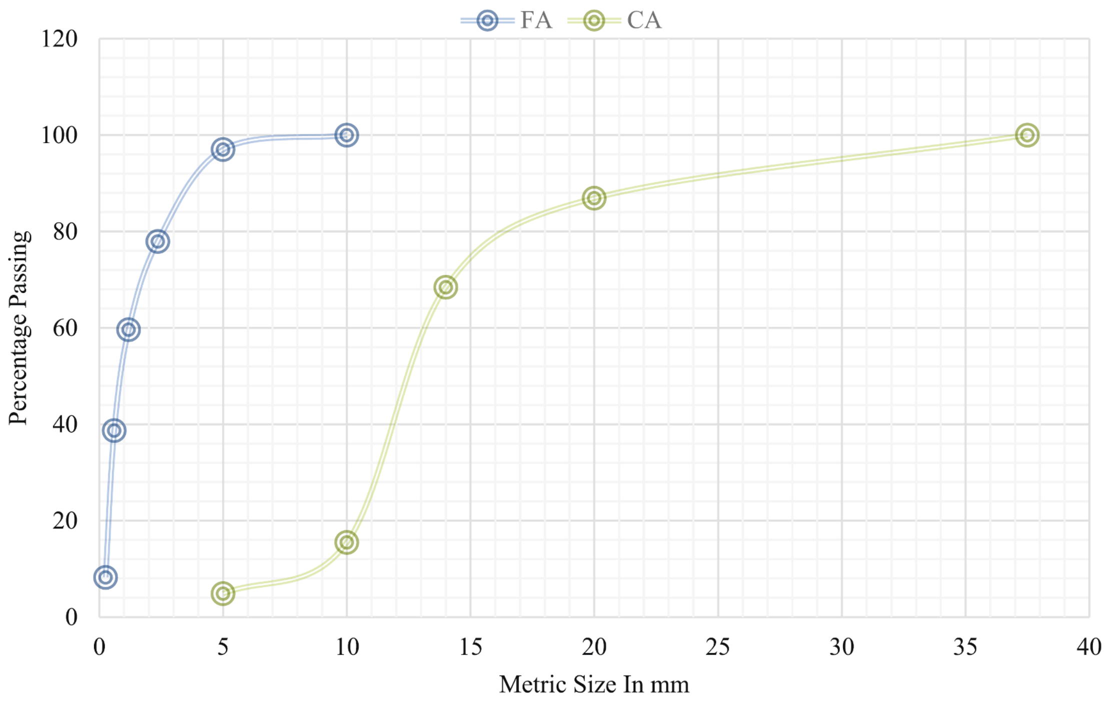


Fig. 6. Sieve Analysis for FA and CA.

Table 3
Properties of PC and MHA.

S.No	Property	PC	MHA
01	Normal Consistency	33 %	38 %
02	Water Absorption	——	25 %
03	SG	3.15	2.25
04	FM	5 %	8 %

mixture. After mixing, the slump test was spotted immediatel under BS EN 12350–2 [26]. The water absorption test was performed on the concrete specimens under BS 1881–122 [27] code at 28 days. Though, the compressive strength was performed on concrete cube (100×100×100 mm) by confirming BS EN 12390–3 [28] while split tensile strength was checked on cylinders (200×100 mm) by obeying BS EN 12390–6 [29]. Moreover, Flexural testing was performed on a concrete prism (500×100×100 mm) with single point loads in accordance with BS EN 12390–5 [30]. In addition, the drying shrinkage was observed on concrete specimens blended with various extents of MHA by the mass of PC in accordance with BS ISO 1920–8 [31] at 40 days.

3. Results and discussions

3.1. Setting time

The setting time describes the rate of strength development, and its importance in concrete hydration cannot be overemphasized. Fig. 8 shows the initial and final setting time of the control and mixed pastes. From the outcome of the study, it has been perceived that the initial and final setting time of the cement slurry is delayed when the substitution level of PC with MHA rises in mortar. Moreover, ASTM C150C150M [32] standard suggested the lowest initial setting time is not exceeded

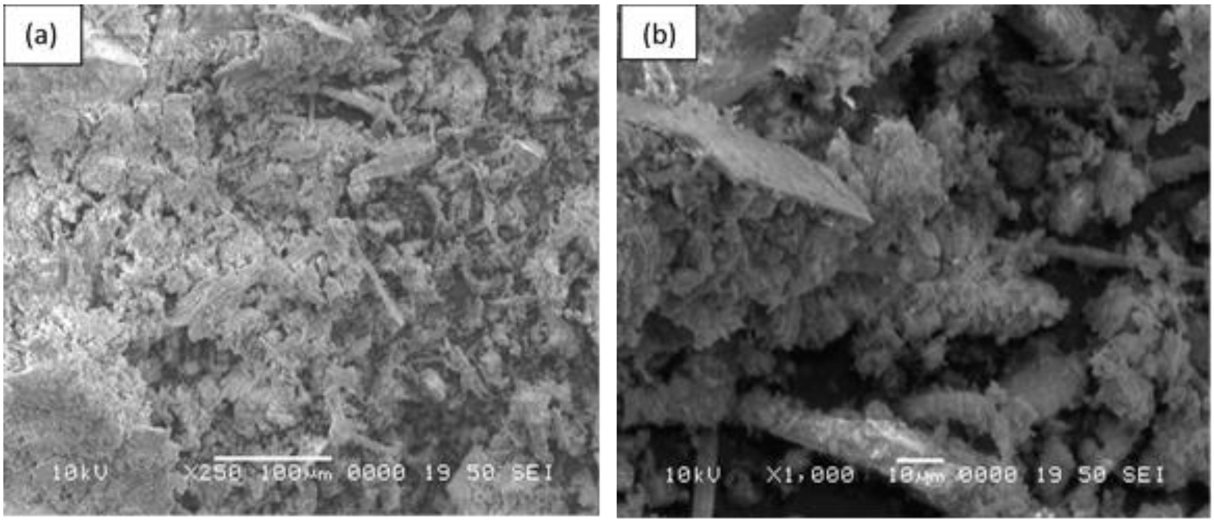


Fig. 7. SEM images of MHA (a) low magnification (b) high magnification.

Table 4
Mixtures composition.

Mixture ID	Binders (%)		Amount of materials used in concrete (kg/m^3)				
	PC	MHA	PC	MHA	FA	CA	Water
0MHA	100	0	375	0	560	1120	202
5MHA	95	5	356.25	18.75	560	1120	202
10MHA	90	10	337.50	37.50	560	1120	202
15MHA	85	15	318.75	56.25	560	1120	202
20MHA	80	20	300	75	560	1120	202

from 48 min while the highest final setting time is not exceeded from 465 min at all level for cement replacement material in mortar. This indicates that MHA may be suitable for materials with a significant delay in setting time. The blocking effect exerted by MHA is similar to other ashes, like palm oil fuel, coconut shell ash with little reactivity [33,34].

3.2. Slump test

Workability is a fresh concrete or mortar attribute which defines how easily and homogeneously it can be consolidated, placed, mixed, and finished with. However, MHA concrete workability decreases with

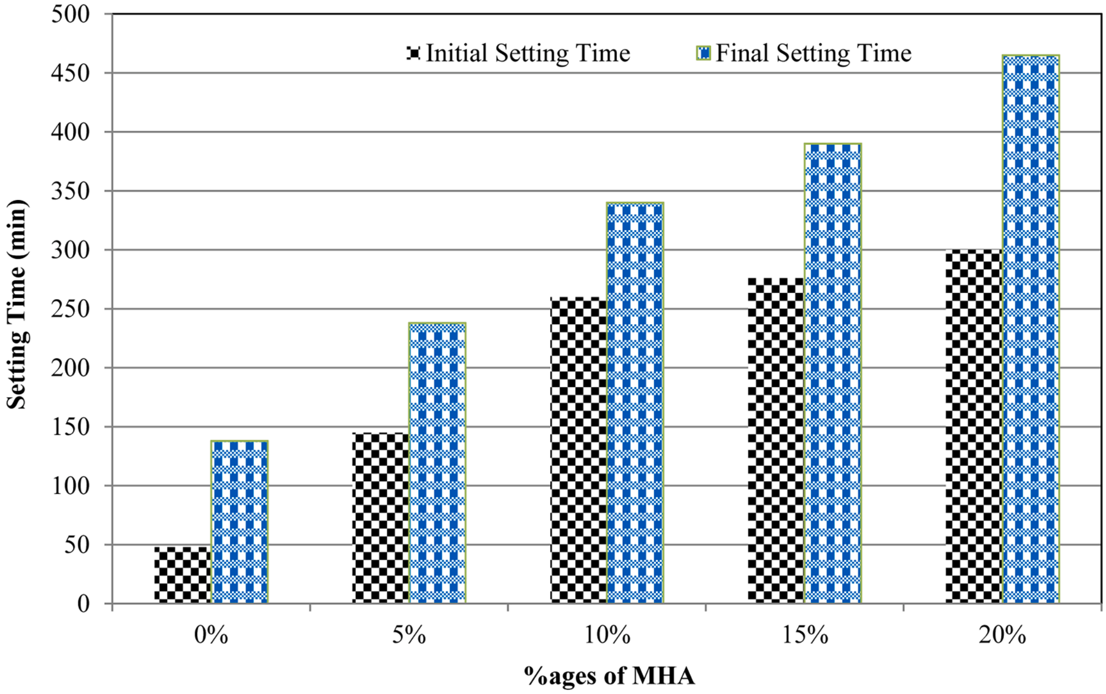


Fig. 8. Setting Time of MHA paste.

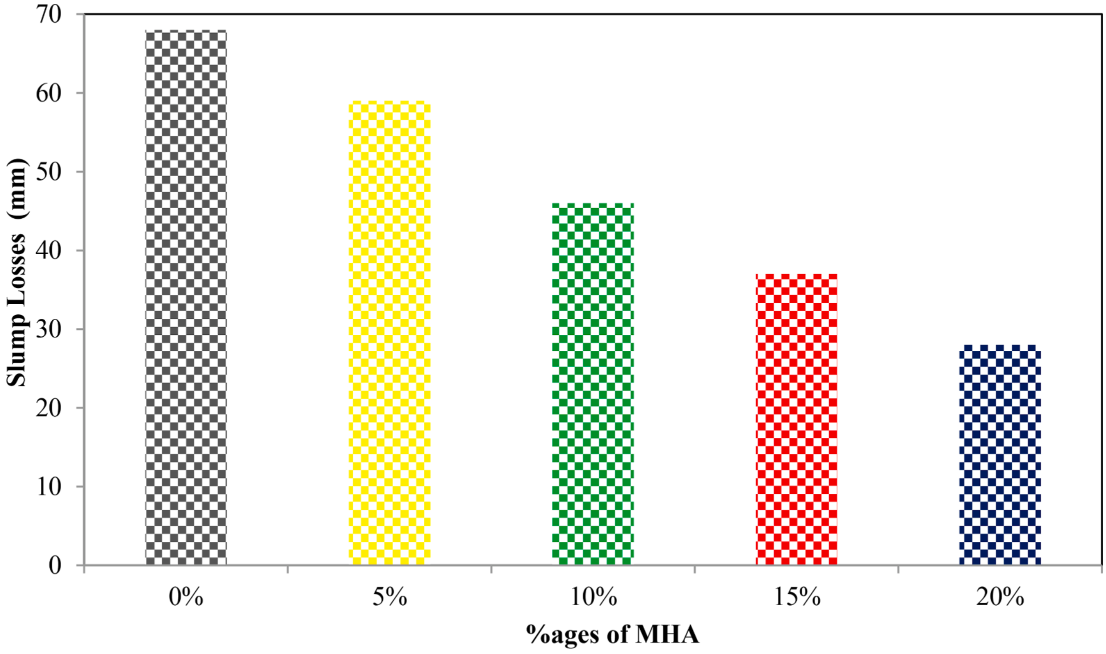


Fig. 9. Workability of concrete containing MHA.

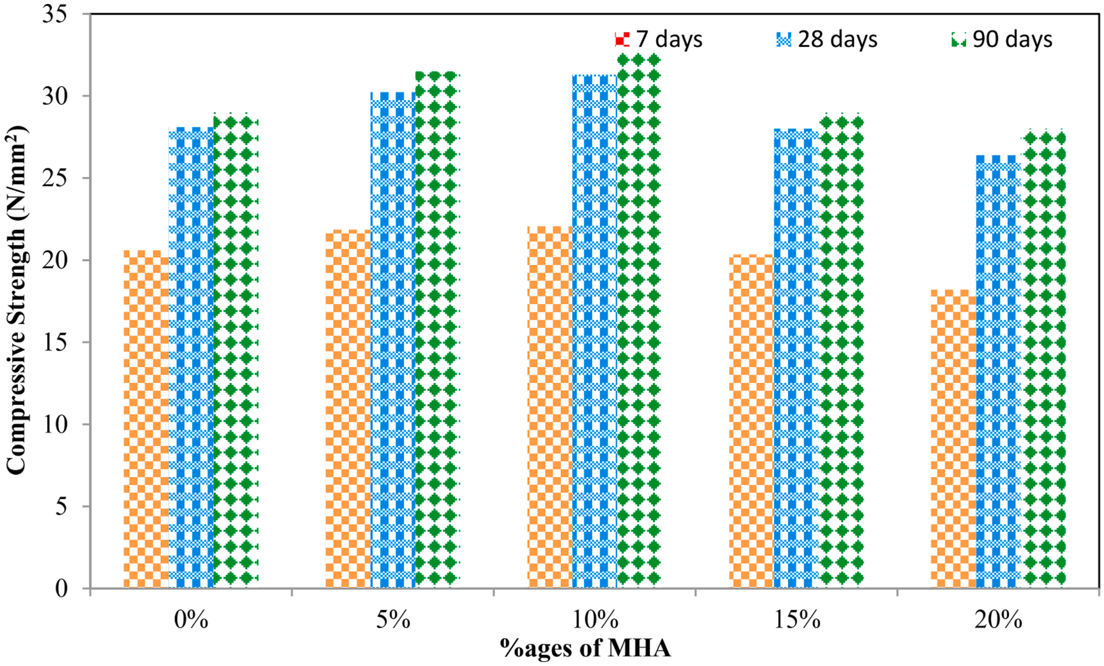


Fig. 10. Compressive strength of concrete containing MHA.

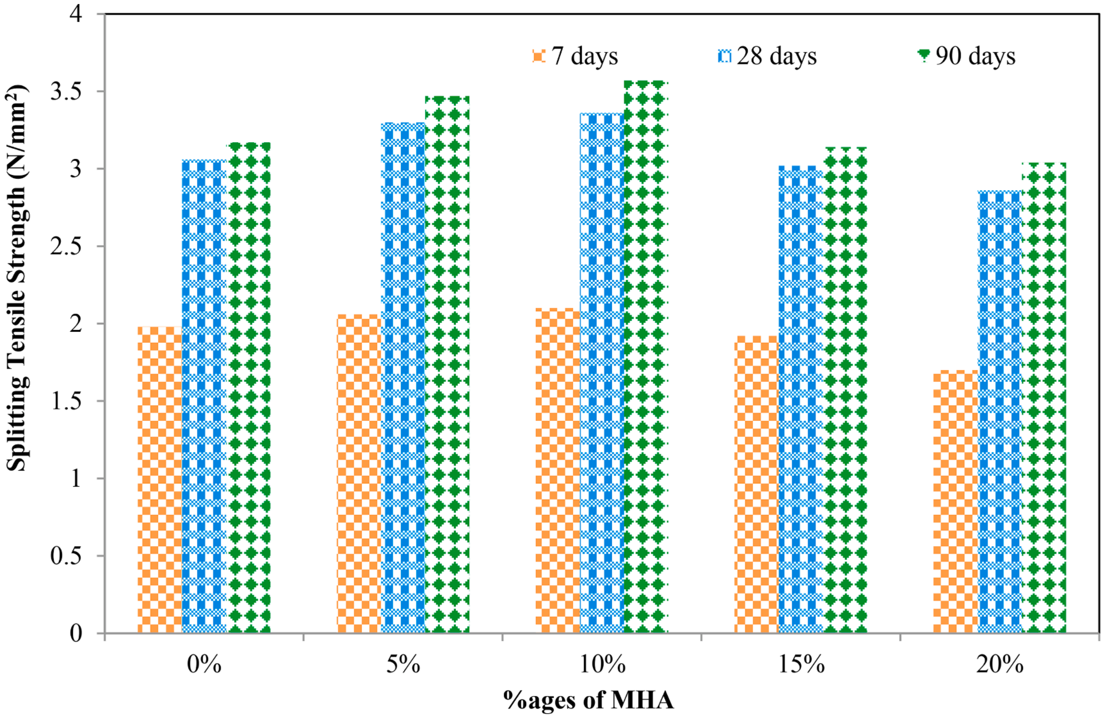


Fig. 11. Splitting Tensile Strength of Concrete containing MHA.

percentage replacement increase with MHA, as revealed in Fig. 9. However, the workability is recorded by 59 mm, 46 mm, 37 mm and 28 mm at 5 %, 10 %, 15 % and 20 % of MHA as PC replacement ingredient which is lower than that of control mixture in mixtures. The workability measured from the slump test illustrates a decrease in slump value, while the proportion of MHA is increased in concrete. Hence there is a need for as much water to make the concrete workable, with an increment in MHA. This decline in workability is associated to the MHA specific surface area is greater than that of PC therefore it absorbs more water as compared to the other ingredients of concrete. This opinion is comparable to Uche et al., [3] that on the effect of MHA on concrete workability are that a decrease in workability following the increment of the MHA proportion, water absorption capacity of MHA with a specific area than cement may not be inconsequential. Bheel et al., [35] documented that the slump is dropped while the replacement of PC with MHA rises in mixture. Relevant investigational work was investigated by Bheel et al [36].

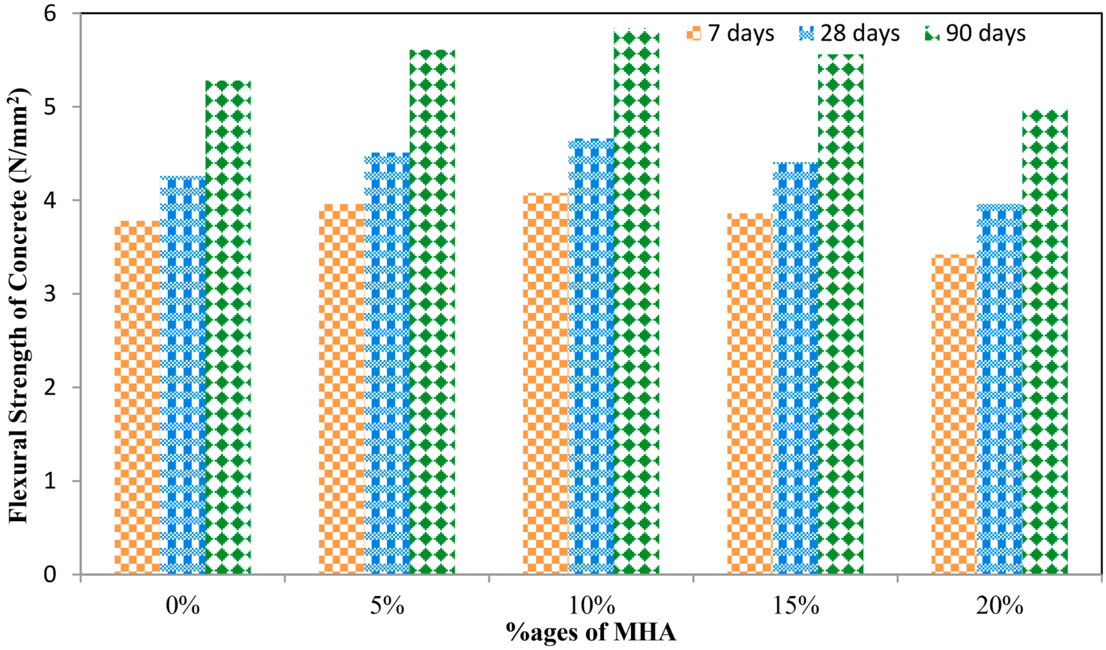


Fig. 12. Flexural Strength of Concrete containing MHA.

3.3. *Compressive strength*

Concrete compressive strength (CS) is a lifeline attribute that is used in concrete technology. All other mechanical parameters like rupture modulus, splitting tensile strength, and elasticity modulus depend directly on the concrete's compressive strength. Compressive strength varies depending on matrix strength, aggregate particle strength, cement content, and the ratio of water to cement [37]. One of the parameters nearly all the researchers include in their investigation is compressive strength. The factors influencing the compressive force of concrete with MHA are the water to cement ratio, duration of curing, and level of MHA replacement from some of these researchers' results analysis. However, Fig. 10 shows average compressive strength for 0 % – 20 % MHA as substitution for PC in mixture at 7, 28 and 90 days. The outcome indicates that the compressive strength of different replacement proportions of MHA generally augmented with an increase in days of curing. It also indicates that the compressive strength increases up to 10 per cent MHA replacement, after which the strength decreases with the percentage of MHA replacement regardless of the hydration period. This development in strength is owing to the large quantity of silica available in MHA and finer MHA particles than PC, which increases the transition zone concrete. As more MHA is added to concrete, the transition zone concrete begins to decrease owing to the dilution effect of MHA on PC, which reduces the calcium hydroxide that is present for product formation [36,38]. This conclusion was reached by Bheel et al. [35], who found that the compressive strength of PC replacement with MHA increased by 10 % at 28 days. Analogous examination was done by Bheel et al., [36]. Auta et al., [24] report 0 per cent, 10 per cent, and 20 per cent replacement compressive strength for 35 days as 32.0, 25.0, and 23.2 N/mm^2 accordingly. This shows reduced strength as the proportion of MHA is increased, making it possible to incorporate MHA in cement in quantity, not exceeding 10 per cent replacement in order to develop good and hard concrete.

3.4. *Splitting tensile strength*

According to Neville, [39], the know-how of tensile strength helps in analyzing the force within which crack causes concrete to fail. This is due to the effect of tensile stress on crack initiation and its propagation into the flexural reinforced concrete member tension region. Concrete is a tension-weak material. So, knowing the tensile strength for concrete used in the design of structures becomes very important. As seen in Fig. 11, the splitting tensile strength (STS) is evaluated by adding 5 to 20 percent MHA as PC substitute material in concrete. The Fig. 11 exposed that the optimum splitting tensile strength is found by 2.1 MPa, 3.36 MPa and 3.57 MPa at 10 % of PC substituted with MHA and smallest strength is calculated by 1.70 MPa, 2.88 MPa and 3.04 MPa at 20 % of MHA as substitution for PC after 7, 28 and 90 days correspondingly. From finding outcomes, it has been indorsed that the STS is increased with growing in the proportion of MHA up to 10 per cent, but subsequently decreased when the PC substitutions level with MHA rises after 10 %. This increment in STS is associated to the MHA surface area as compared to PC which boosts the interfacial transition zone of concrete up to 10 % and further accumulation of MHA in concrete, it gets decline owing to the lesser pozzolanic reaction of MHA than that of hydration reaction of PC in concrete. This conclusion was reached by Bheel et al. [35], who found that the indirect tensile strength augmented by 10 % when PC was substituted with MHA, and further addition of MHA, it began to decrease at 28 days. Comparable research was conducted by Bheel et al [36].

3.5. *Flexural strength*

The general pattern for the flexural tensile strength of concrete comprising MHA followed the tensile splitting force pattern. The optimum flexural strength (FS) was calculated by 7.94 %, 9.38 %, and 10.60 % at 10 % of MHA, and the smallest value was noted by 9.52 %, 7.04 % and 5.87 % while 20 % of MHA after 7, 28, 90 days respectively. The flexural strength was observed from the results presented in Fig. 12 that the flexural strength of concrete is increased while applying MHA as substitutions for PC up to 10 per cent and the further accumulation of it in mixture, the strength gets plummeting. This increment in bending tensile strength was owing mainly to the filling capability of finer MHA particles, similar to the strength of the splitting tensile. After 10 % of MHA, it gets dropping owing to the addition of MHA in concrete, which can be endorsed to the dilution effect of PC and the slow pozzolanic reaction of MHA [35,38]. This conclusion was reached by Bheel et al. [35], who found that the flexural strength augmented by 10 % when PC

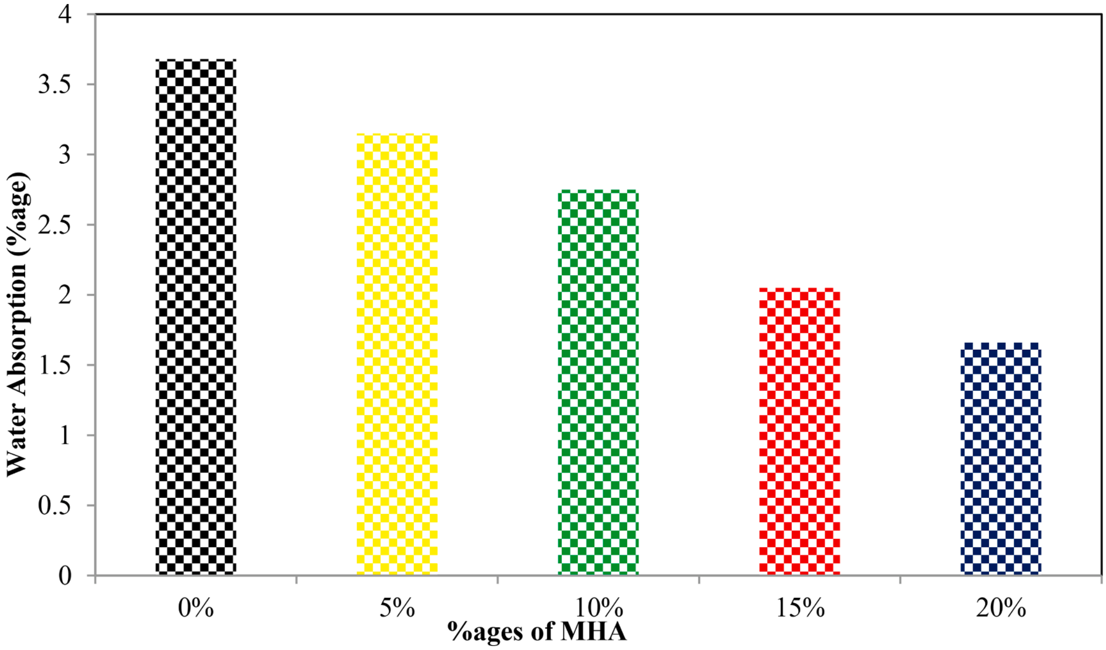


Fig. 13. Water Absorption of Concrete containing MHA at 28 days.

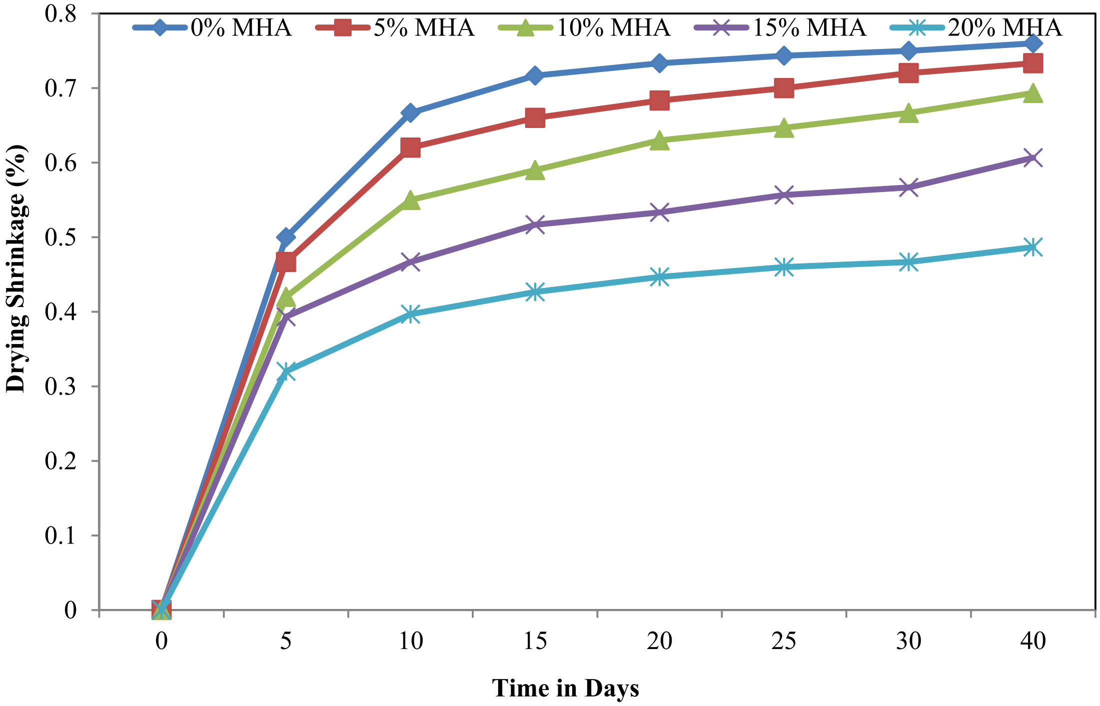


Fig. 14. Drying Shrinkage of Concrete containing MHA.

was replaced with MHA, and further addition of MHA, it began to decrease at 28 days. Comparable examination was carried out by Bheel et al., [36] that the utilization of MHA up to 10 % as substitution for PC is providing optimum outcomes after 28 days.

Table 5
Embodied Carbon of concrete components.

Components	Embodied Carbon (kgCO$_2$/kg)	References
PC	0.82	[47]
FA	0.0139	[48]
CA	0.0408	[48]
MHA	0.174	[38]
Water	0	[49]

3.6. Water absorption

The concrete specimens were prepared of concrete accumulation with different extents of MHA as PC replacement constituent for analysing the water absorption (WA) of concrete after 28 days as presented in Fig. 13. The finding was directed that the water absorption is

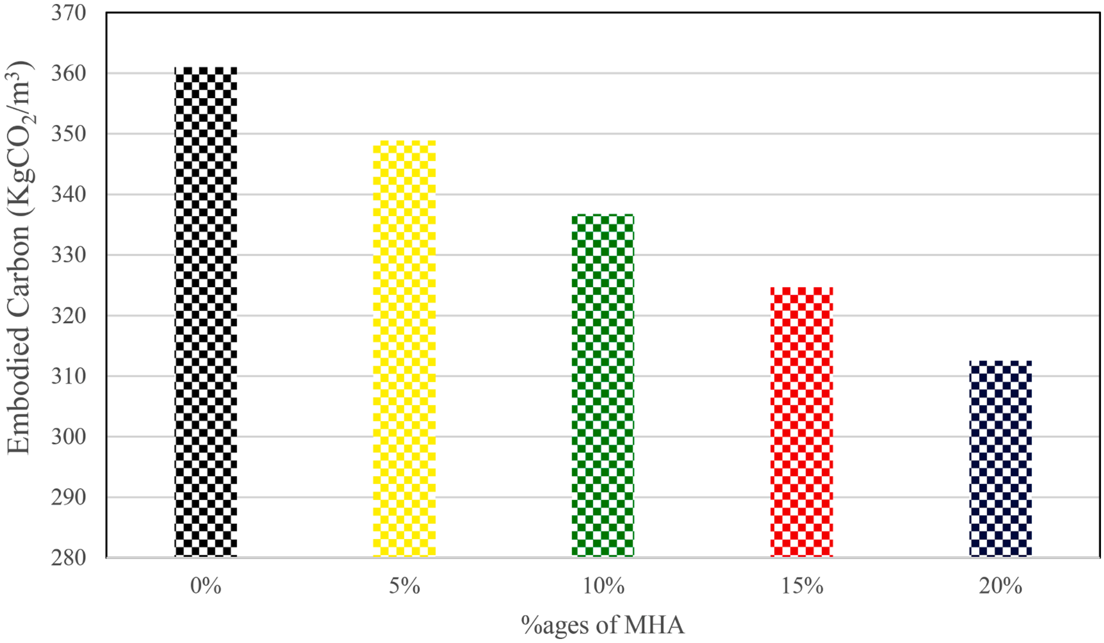


Fig. 15. Embodied Carbon of Concrete containing MHA.

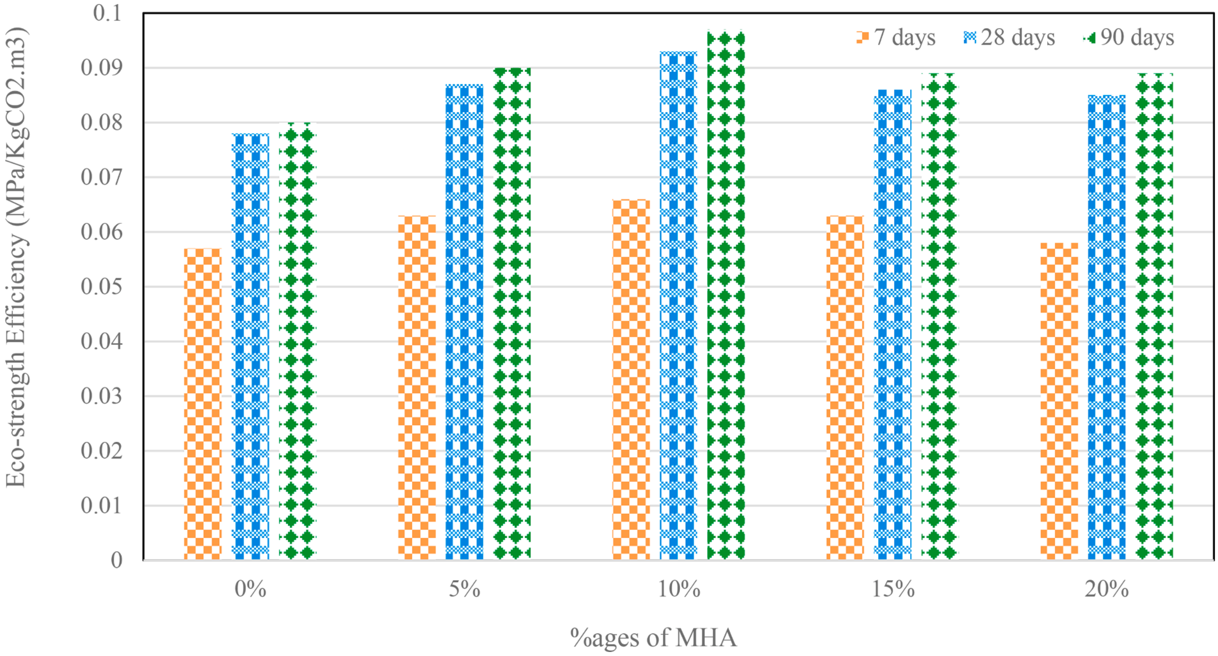


Fig. 16. Eco-strength Efficiency of concrete containing MHA.

calculated by 14.40 %, 25.27 %, 44.29 % and 54.89 % at 5 %, 10 %, 15 %, and 20 % of MHA is lesser as compared to concrete with addition 0 % of MHA as PC replacement constituent on 28 days, correspondingly. Therefore, it was discovered that the water absorption was declined as the extent of MHA growths in mixture of concrete. This could be a result of the densification of the sample due to the pozzolanic reaction of PC with MHA. Moreover, the concrete water absorption is reduced while the extents of MHA as cementitious component growths in mixture after every curing days. This drop in water absorption is associated to more fineness of MHA than that of PC which reduces concrete porosity at higher MHA content. This remark is interrelated with Bheel et al., [40] where the water absorption was decreased with growing in the quantity of marble powder and tile powder in concrete on 28 days. Comparable investigation was done by Bheel et al., [35] that the substitution of MHA by the mass of PC increases in concrete that reults in dropping the water absorption of mixture at 28 days.

3.7. Drying shrinkage

Fig. 14 shows drying shrinkage (DS) of concrete is getting decrease as the percentage composition of MHA increases at different curing days, but increases when the percentage of MHA replacement increases. This outcomes in dramatic decline shrinkage at drying when MHA is utilized in concrete as a substituted for PC as compared to control mix; and this reduction is associated with an addition of substituted PC with MHA. This can be related to low cement proportion as compared with the

Table 6
ANOVA.

Response	Source	Sum of Squares	Df	Mean Square	F-Value	p-value > F	Significance
Compressive Strength	Model	17.93	2	8.97	16.91	0.0112	**Yes**
	A-MHA	4.52	1	4.52	8.53	0.0432	**Yes**
	A^2	13.41	1	13.41	25.30	0.0073	**Yes**
	Residual	2.12	4	0.53			
	Lack of Fit	2.12	2	1.06			
	Pure Error	0.000	2	0.000			
	Cor Total	20.05	6				
Splitting Tensile Strength	Model	0.19	2	0.093	13.95	0.0157	**Yes**
	A-MHA	0.056	1	0.056	8.36	0.0445	**Yes**
	A^2	0.13	1	0.13	19.53	0.0115	**Yes**
	Residual	0.027	4	6.647E-003			
	Lack of Fit	0.026	2	0.013	32.24	0.0301	**Yes**
	Pure Error	8.000E-004	2	4.000E-004			
	Cor Total	0.21	6				
Flexural Strength	Model	0.41	2	0.21	175.13	0.0001	**Yes**
	A-MHA	0.094	1	0.094	79.33	0.0009	**Yes**
	A^2	0.32	1	0.32	270.93	< 0.0001	**Yes**
	Residual	4.734E-003	4	1.184E-003			
	Lack of Fit	4.734E-003	2	2.367E-003			
	Pure Error	0.000	2	0.000			
	Cor Total	0.42	6				
Water Absorption	Model	4.68	1	4.68	1213.80	< 0.0001	**Yes**
	A-MHA	4.68	1	4.68	1213.80	< 0.0001	**Yes**
	Residual	0.019	5	3.857E-003			
	Lack of Fit	0.019	3	6.429E-003			
	Pure Error	0.000	2	0.000			
	Cor Total	4.70	6				
Drying Shrinkage	Model	0.094	2	0.047	487.26	< 0.0001	**Yes**
	A-MHA	0.091	1	0.091	942.08	< 0.0001	**Yes**
	A^2	3.134E-003	1	3.134E-003	32.44	0.0047	**Yes**
	Residual	3.865E-004	4	9.662E-005			
	Lack of Fit	3.865E-004	2	1.932E-004			
	Pure Error	0.000	2	0.000			
	Cor Total	0.095	6				

Table 7
Parameters for Model Verification.

Model Validation Constraints	CS	STS	FS	WA	DS
Std. Dev.	0.73	0.082	0.034	0.062	9.829E-003
Mean	28.36	3.08	4.29	2.66	0.63
C.V. %	2.57	2.65	0.80	2.33	1.57
PRESS	5.78	0.069	0.013	0.029	1.038E-003
−2 Log Likelihood	11.50	−19.15	−31.23	−21.39	−48.77
R-Squared	0.8943	0.8746	0.9887	0.9959	0.9959
Adj R-Squared	0.8414	0.8119	0.9831	0.9951	0.9939
Pred R-Squared	0.7115	0.6727	0.9680	0.9938	0.9890
Adeq Precision	9.025	8.164	29.064	61.451	44.203
BIC	17.34	−13.31	−25.39	−17.50	−42.93
AICc	25.50	−5.15	−17.23	−14.39	−34.77

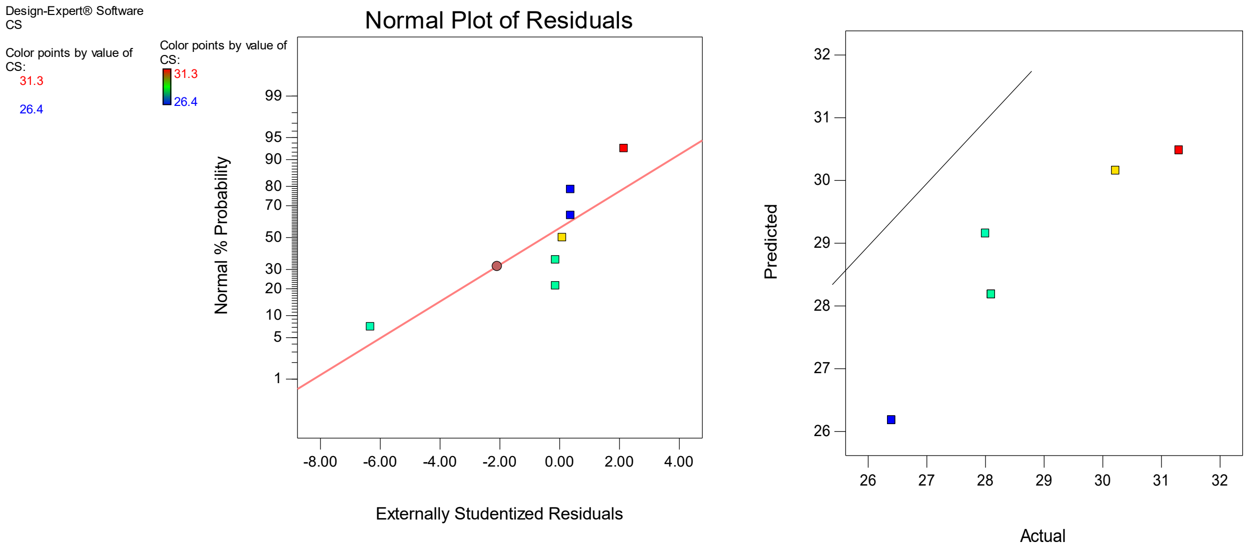
control mix, and also the processes of pore size and grain size refinement that enhance adhesion strength within the transition zone. Therefore, MHA can be used as part of its mitigation strategy when shrinking is a concern. This similar kind of examination was explored by Bheel et al., [41] that the drying shrinkage is reduced whereas the replacement of PC with binary cementitious material rises in concrete. Literature studies were stated that the drying shrinkage is declined while the usage of RHA as SCM rises in cocrete [42–46].

4. Sustainability assessment

The embodied carbon of concrete accumulation with MHA as cementitious material was assessed for all mixes in this research project to determine the environmental impact. As shown in Table 5, the embodied carbon of concrete ingredients were collected from the previous studies. However, Eq. (1) can be applied to evaluation the embodied CO_2 for five concrete mixes. In Eq. (1), the signs CO_{2e}, i and W_i denote total embodied carbon and weight per unit volume (kg/m^3) for each concrete mix. Furthermore, the symbol CO_{2i} has been used to represent the embodied carbon of the concrete constitutions recorded in Table 5.

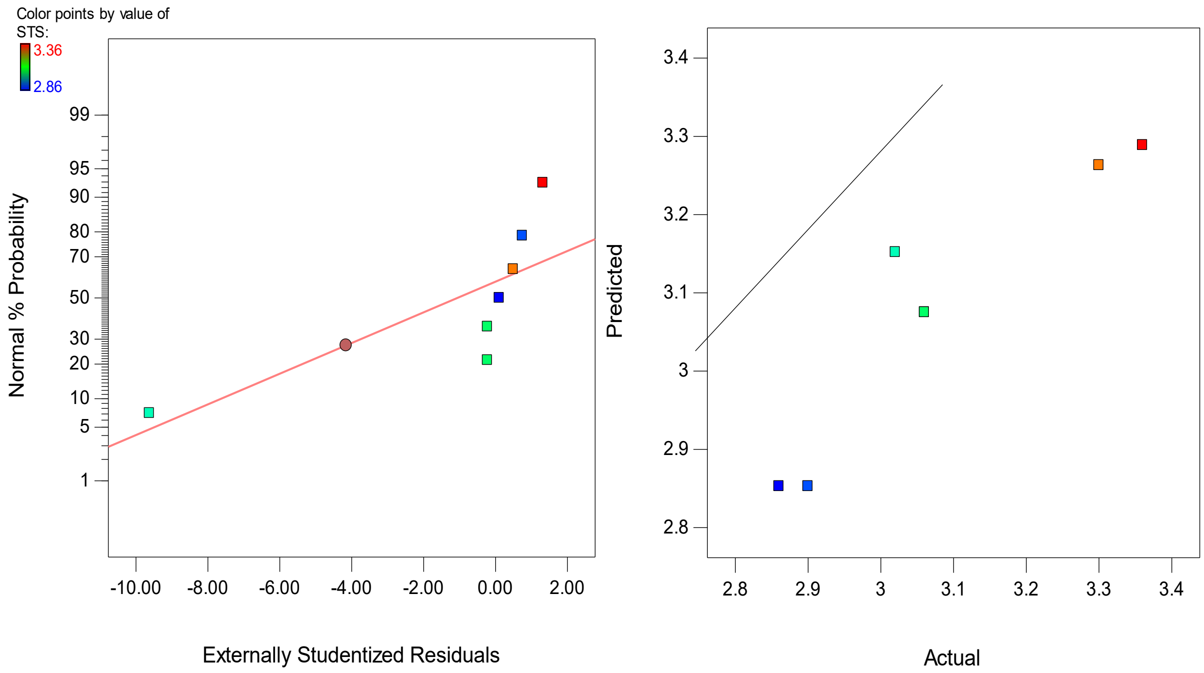
$$CO_{2e} = \sum_{i=1}^{n} (W_i \times CO_{2i}) \tag{1}$$

Fig. 15 demonstrations the embodied carbon in concrete, which includes MHA as a cementitious ingredient. Fig. 15 reveals that Portland cement releases the most carbon, followed by CA and FA. Though, the involvement of MHA as a PC substitution material in mixture is small as revealed in Fig. 15, resulting the influence of MHA as a substitution for PC is too small to the embodied carbon. The embodied carbon is calculated by 3.36 %, 6.71 %, 10.10 % and 13.42 % at 5 %, 10 %, 15 % and 20 % of MHA as substitution for PC is lesser as contrasted to control mix correspondingly. The embodied carbon has been observed to decrease with growing in the extent of MHA as substitutions for PC in concrete. An analogous kind of investigation was explored by Bheel et al. [38] that the embodied carbon is declined while the substitution extents



(a) (b)

Fig. 17. (a) Normal Plot of Residuals (b) Predicted versus Actual Plot for CS.



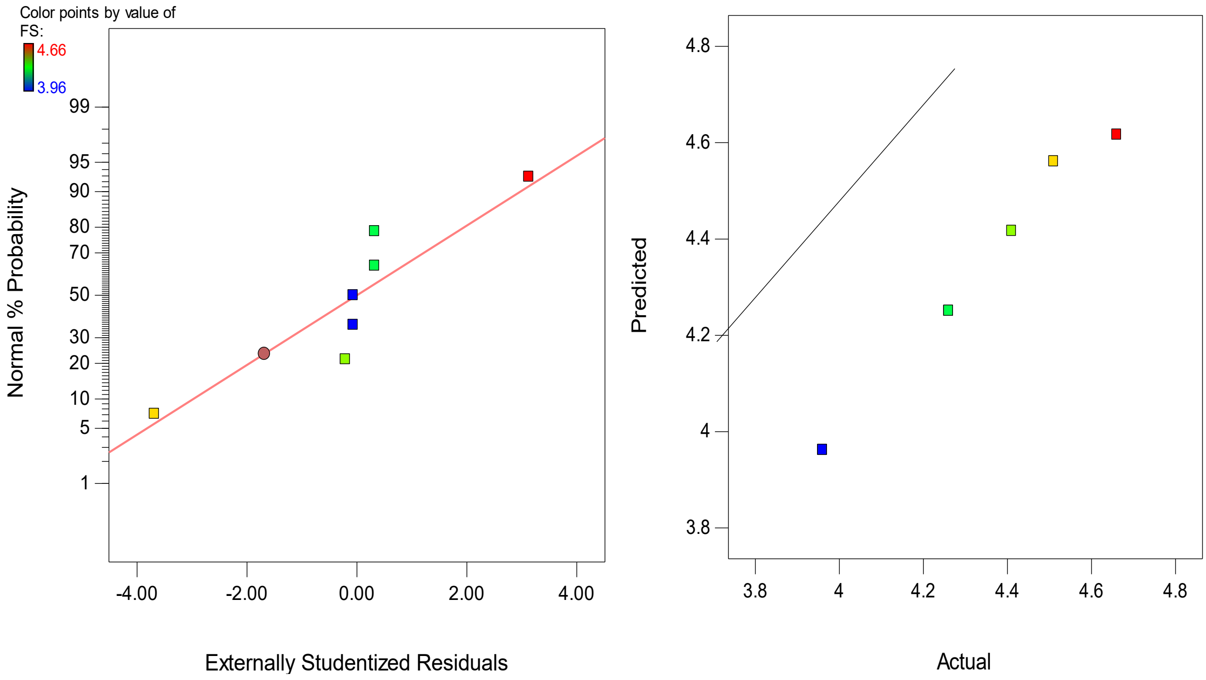
(a) (b)

Fig. 18. (a) Normal Plot of Residuals (b) Predicted versus Actual Plot for STS.

of PC with MHA growths in concrete. Comparable work was directed by Keerio et al. [50] that the use of MK as substitution for PC in concrete is plummeted the embodied carbon. Moreover, not only decrease in embodied carbon would be targeted, but also the decrease in ingredients associated with the substitution of PC with MHA, as well as the influences of these waste products on compressive strength. Eq. (2) can be applied to well understand this by using an eco-strength efficiency indicator.

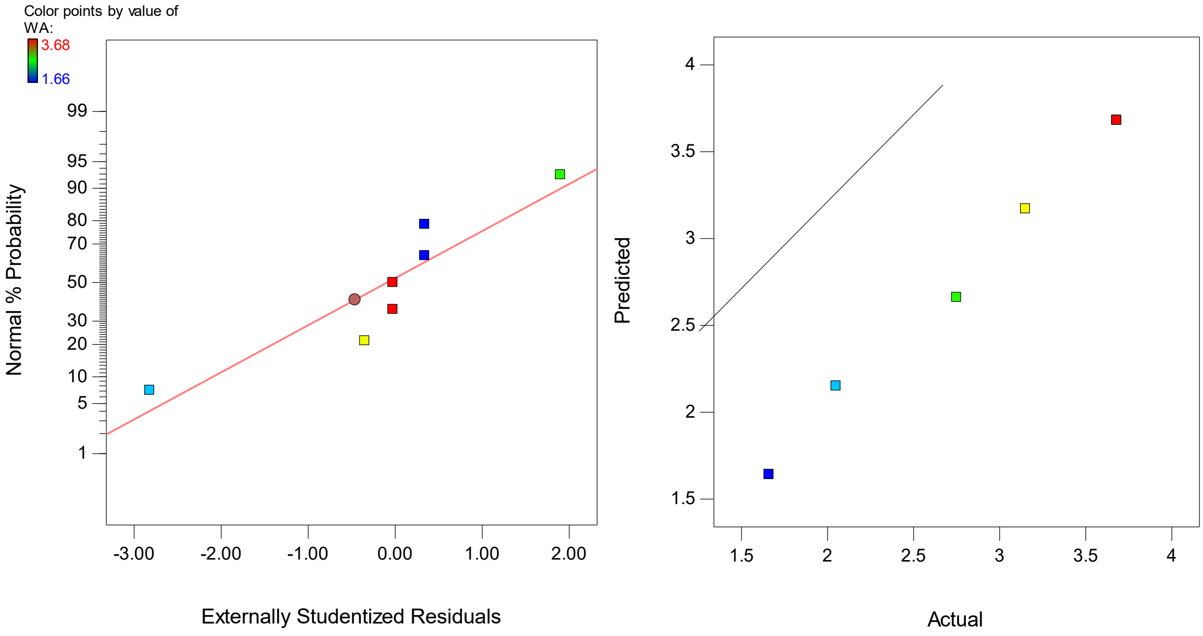
$$Eco-strengthEfficiency=\frac{Average28-DaysCompressiveStrengthofConcrete}{TotalEmbodiedCarbonofConcrete} \tag{2}$$

Eq. (2) was used to calculate the eco-strength efficiency of concrete accumulation with MHA by the mass of PC, and the result is presented in Fig. 16. The greater eco-strength efficiency was recorded by 0.066 MPa/kgCO$_2$.m^3, 0.093 MPa/kgCO$_2$.m^3 and 0.097 MPa/kgCO$_2$.m^3 at 10 % of PC substituted with MHA in concrete at 7, 28 and 90 days correspondingly. However, the smallest eco-strength efficiency strength was considered by 0.058 MPa/kgCO$_2$.m^3, 0.085 MPa/kgCO$_2$.m^3 and 0.089



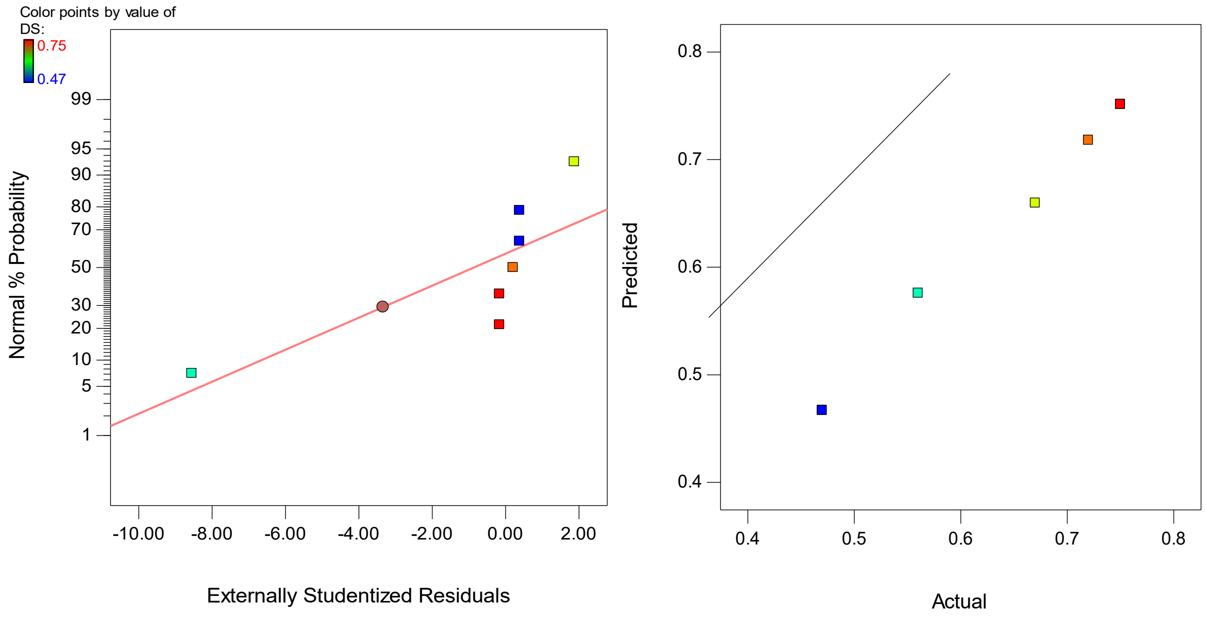
(a) (b)

Fig. 19. (a) Normal Plot of Residuals (b) Predicted versus Actual Plot for FS.



(a) (b)

Fig. 20. (a) Normal Plot of Residuals (b) Predicted versus Actual Plot for WA.



(a) (b)

Fig. 21. (a) Normal Plot of Residuals (b) Predicted versus Actual Plot for DS.

Table 8
Optimization goals and outcomes.

Factors		Input Factors	Response (Output Factors)				
		MHA (%)	CS (MPa)	STS (MPa)	FS (MPa)	WA (&)	DS (%)
Value	Min.	0	26.40	2.86	3.96	1.66	0.47
	Max.	20	31.30	3.36	4.66	3.68	0.70
Goal		Range	Max.	Max.	Max.	Min.	Min.
Optimization Results		12.46	30.03	3.24	4.55	2.41	0.62
Desirability			0.673 (67.3 %)				

MPa/kgCO_2.m^3 at 20 % of MHA as cementitious ingredient in concrete at 7, 28 and 90 days correspondingly. It was discovered that when the percentage of PC substituted with MHA in concrete grows to 10 %, the eco-strength efficiency improves, and as more MHA is added, the eco-strength efficiency decreases. The comparable work was directed by Bheel et al. [38] that the eco-strength efficiency is increased whereas the utilization of MHA up to 10 % as substitutions for PC in concrete after 28 days. This is owing to the lowest carbon content and highest compressive strength of the various mixes.

5. RSM modelling and optimization

5.1. Response surface models development and ANOVA

RSM is used to develop a response surface model and evaluate it utilizing analysis of variance (ANOVA). However, the mechanical characteristics of concrete mixes using 0 % to 20 % MHA as a cement alternative were investigated for RSM modelling and optimization. Furthermore, quadratic models are better suited for CS, STS, FS, and DS, but linear models are better suited for water absorption response. Furthermore, in Eqs. (1) to (5), each of these replies is represented by a coded term. Equations stated in coded elements may predict a distinct number of outcomes for each variable. The greatest level of an element is represented as +1 by default, while the lowest level is represented as −1. By calculating factor coefficients, coding equations may be utilised to evaluate the relative significance of variables. A is also an input factor (MHA). Table 6 displays the findings of the analysis of variance.

The significance threshold for ANOVA was set at 95 %, and any design or model constituent with a probability of <5 % is measured noteworthy. All produced models are statistically important in this respect, since their probabilities are <0.05. Individual variables A and A^2 in the compressive strength model are statistically significant. Individual model terms A and A^2 are statistically important for the compressive strength model. As a result, A and A^2 are crucial model parameters for the STS, FS, and DS models. A is also an essential model term in the water absorption model. The determination coefficient is an important performance metric (R^2). The R^2 statistic, which may be stated as a percentage or as a number ranging from 0 to 1, analyses the model's fit with empirical data (0 to 100 percent). The better the fit, the higher the value, and vice versa. Table 6 displays R^2 and other model evaluation factors. All of the models had a high R^2, with values for CS, STS, FS, WA and DS of 98.43 percent, 87.46 percent, 98.87 percent, 99.59 percent, and 99.59 percent, respectively. In addition, “Adeq Precision” calculates the signal-to-noise ratio. A ratio larger than 4 is preferred. The Adeq. precision values for the CS, STS, FS, WA and DS models are 9.03, 8.16, 29.06, 61.45, and 44.20, respectively, as shown in Table 7. This data demonstrates that the models are valid and may be applied to accurately anticipate responses.

$$CS = +30.48 - 1.00 \times A - 3.30 \times A^2 \tag{1}$$

$$STS = +3.29 - 0.11 \times A - 0.32 \times A^2 \tag{2}$$

$$FS = +4.62 - 0.14 \times A - 0.51 \times A^2 \tag{3}$$

$$WA = +2.66 - 1.12 \times A \tag{4}$$

$$DS = +0.66 - 0.14 \times A - 0.050 \times A^2 \tag{5}$$

The “Normal vs Residual” and “Actual vs Predicted” plots, as illustrated in Figs. 17-21 for the five variables, are useful model diagnostic tools for assessing the condition and application of the developed response models (CS, STS, FS, WA, and DS). The linearity of the data sets along the fit line in each graph illustrates the correctness of the built

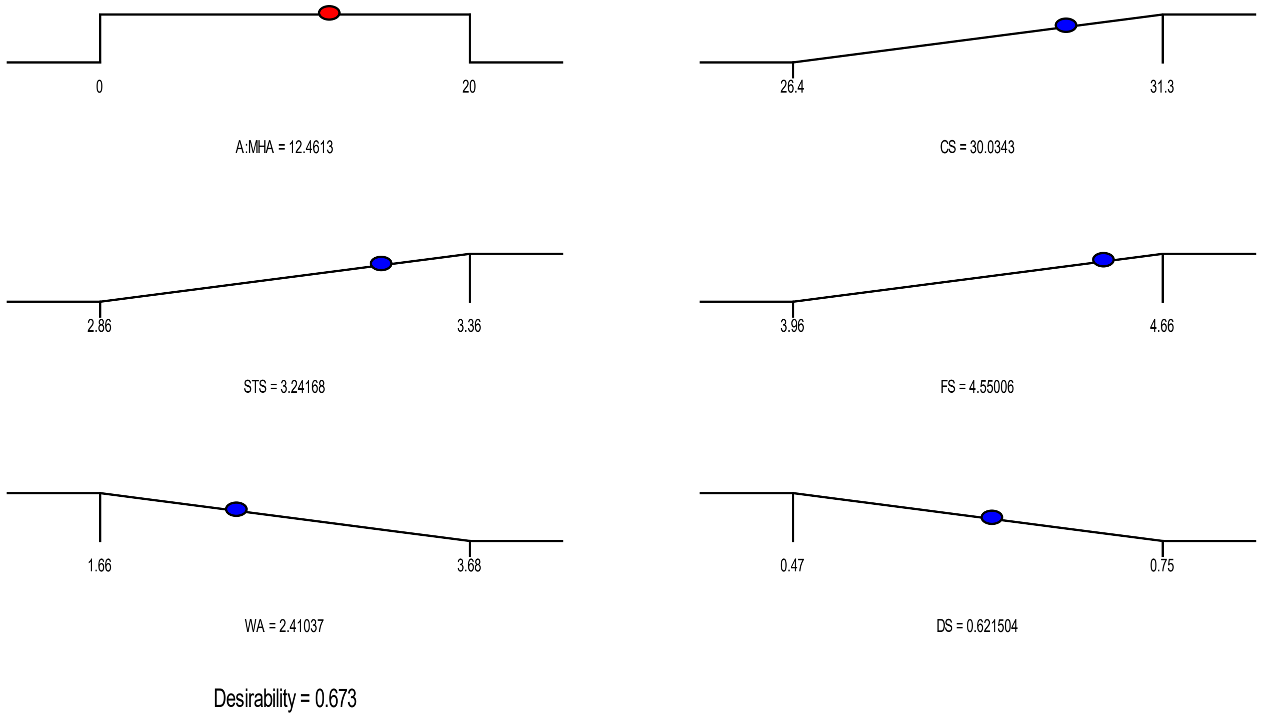


Fig. 22. Optimization solution ramp.

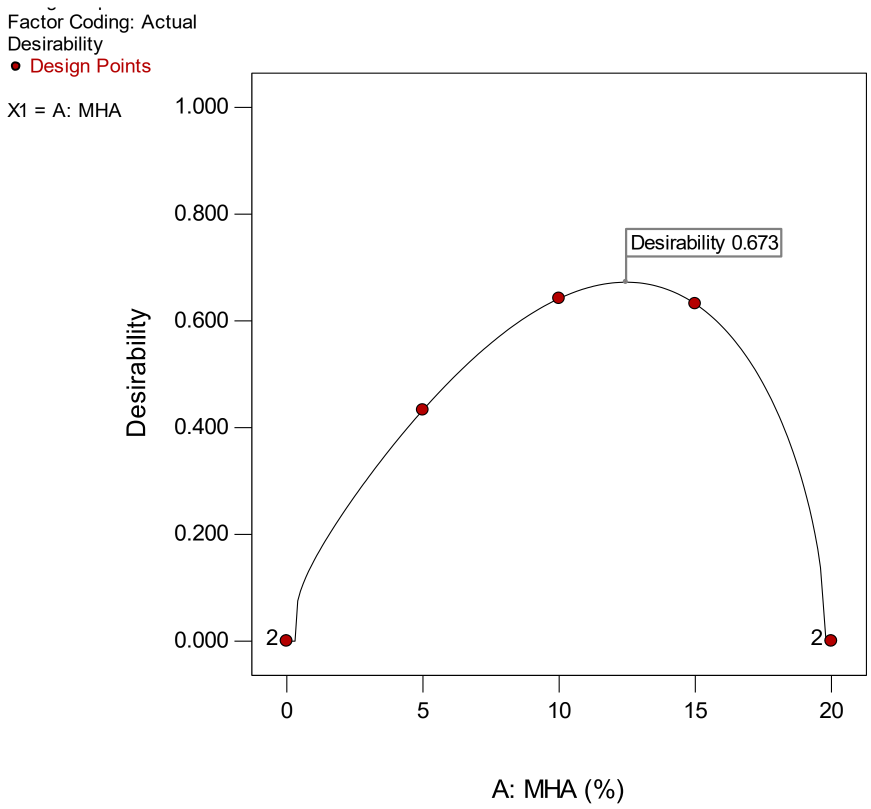


Fig. 23. One Factor response surface diagram for the desirability of the optimization.

models. The normal plots of the residuals' data points reveal a pattern of data points that suggests the error terms are normally distributed, which is preferred. As with the previous models [51,52], residuals are frequently distributed if 95 percent of the points fall between −2 and +2.

5.2. Optimization

An optimization is carried out to determine the optimal values of the independent elements that result in the highest percentages of desired results. Setting objectives for the functions (inputs and outputs) with shifting criteria and relevance levels to attain the desired function is how this is executed. Using the anticipated values values ($0 \leq$ dj ≤ 1), assess the optimization. The higher the value, the stronger the outcome. Table 8 describes the objectives and criteria for this optimization example. The optimization aim, as stated in Table 6, is to maximise three replies and minimize two responses. Moreover, the usage of MHA is restricted to a range of 0 % to 20 % by mass of cement, allowing the system to select the ideal quantity to accomplish its purpose. The optimization results showed that integrating 12.48 percent MHA as a substitution for PC in the concrete resulted in the optimum values of 30.03 MPa, 3.24 MPa, 4.55 MPa, 2.41 percent, and 0.62 percent for the CS, STS, FS, WA, and DS, correspondingly. The optimization's desirability was examined to be 67.3 percent, which is pretty realistic given the nature of the huge fluctuations in response values. Figs. 22 and 23 depict, respectively, the best solution for desirability and the one-factor response surface diagram.

6. Conclusion

The use of MHA as SCM in eco-friendly concrete is investigated in this study. The impact of MHA on the fresh concrete, hardened properties and drying shrinkage of concrete was investigated using concrete samples containing various percentages of MHA and tested at various ages. The following are the findings of the research:

- The initial and final setting time of MHA paste was increased with rising in the content of MHA. The highest slump value of concrete was recorded by 68 mm inclusion with 0 % of MHA and the lowest slump value was noted by 28 mm while using 20 % cement was replaced with MHA in concrete.
- The value of compressive strength was augmented by 7.1 %, 11.39 % and 12.93 % by using 10 % of MHA and lowest strength noted by 11.65 %, 6.04 % and 3.57 % while using 20 % of PC replaced with MHA in mixture at 7, 28 and 90 days correspondingly. However, the split tensile strength was improved by 6.10 %, 9.80 % and 12.62 % by using 10 % of MHA and least value was recorded by 14.14 %, 6.54 % and 4.1 % by using 20 % cement was replaced with MHA in concrete mixes at 7, 28 and 90 days correspondingly.
- The flexural strength was enhanced by 7.94 %, 9.39 % and 10.61 % by using 10 % of MHA and minimum value was recorded by 9.52 %, 7.04 % and 5.87 % while using 20 % cement was replaced with MHA in mixture on 7, 14 and 28 days correspondingly. As the amount of MHA in concrete grew, the modulus of elasticity increased as well.
- The optimum water absorption was performed by 3.68 % at 0 % of MHA, and the lowest water absorption was noted by 1.66 % when using 20 % of PC substituted with MHA in mixture of concrete on 28th days.
- The drying shrinkage of concrete was enhanced with an increase in the amount of MHA in concrete after 40 days.
- The eco-strength efficiency of concrete is boosted when the percentage of PC replaced with MHA in concrete grows to 10 %, and as more MHA is added, the eco-strength efficiency decreases after 7, 28 and 90 days correspondingly.
- ANOVA was used to develop the response surface models for predicting mechanical characteristics. However, the R^2 value for compressive strength, splitting tensile strength, flexural strength, water absorption, and drying shrinkage models were 98.43 %, 87.46 %, 98.87 %, 99.59 %, and 99.59 %, respectively. Moreover, the accumulation of 12.48 % MHA as a cementitious ingredient in a concrete mixture that results in achieving 67.30 % of desirability factor. The experimental validation revealed a statistically significant relationship between predicted and actual results, with <5 % error for each of the five investigated responses.
- Based on the experimental study, it is recommended that the use of MHA in concrete up to 10 % provides best results for structural applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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