EVALUATING THE PROPERTIES OF MUSSEL SEA SHELL LIGHTWEIGHT FOAM CONCRETE: EMPHASIZING SUSTAINABILITY AND WASTE REDUCTION

Shuvo Dip Datta*[1], Aswad Siddiqua Nirjona[2], Md. Rafi Azam[3] and Md. Shakib Shah[4]

[1] *Lecturer, Khulna University of Engineering & Technology, Bangladesh, e-mail: sd.datta@becm.kuet.ac.bd*
[2] *Undergraduate student, Khulna University of Engineering & Technology, Bangladesh, e-mail: nirjona1923056@stud.kuet.ac.bd*
[3] *Undergraduate student, Khulna University of Engineering & Technology, Bangladesh, e-mail: azam1923047@stud.kuet.ac.bd*
[4] *Undergraduate student, Khulna University of Engineering & Technology, Bangladesh, e-mail: shah1923054@stud.kuet.ac.bd*

ABSTRACT

Emphasizing the optimal utilization of aquaculture waste in lightweight building structures, it is essential to thoroughly investigate the complete range of characteristics of waste mussel shell ash (MSA) in lightweight foamed concrete (LFC). This study aims to determine the fresh, mechanical, and MSA-based LFC. To assess the impact of replacing 5%, 10%, 15%, 20%, 25%, and 30% of the cement with seashell ash, six LFC mixtures were created and compared against the control mix. The study offers an overview of the mechanical, environmental, and cost-benefit characteristics of the LFC in the detailed properties. Furthermore, the study demonstrates that substituting 15% of MSA enhances compressive, flexural, and splitting tensile strengths by up to 12.41%, 15.89%, and 17.95%, respectively, in contrast to the standard mix. The research also introduces a new dimension by incorporating sustainability and cost analysis, which will contribute to the advancement of foam concrete application-based studies. Considering the comprehensive perspective, a 15% substitution of seashell-based MSA concrete appears to be the most suitable choice for sustainable concrete production.

Keywords: *Foam Concrete, Mussel Shell Ash, Cost Efficient, Compressive Strength, Sustainability.*

1. INTRODUCTION

Concrete is chosen worldwide in construction compared to other materials due to its enormous variety of applications (He et al., 2019). The traditional binder in concrete is cement, which is also the most costly (Kassim & Ong, 2019). Studies indicate yearly cement production exceeds 4 billion metric tons, with an average of 0.56 tons per person since 2017. Cement demand and production are predicted to rise with the increasing world population (Olutoge et al., 2016; Peow et al., 2014).

During the production of clicker, the primary element of OPC, vital greenhouse gases are emitted due to the breakdown of limestone and fossil fuels. (Shanks et al., 2019). The fossil fuels are burned to heat the limestone at temperatures ranging from 1450°C - 1500°C. The combustion of fossil fuels accounts for 40–50% of emissions, while limestone heating contributes to the remaining 50–60%. (Peow et al., 2014; Shanks et al., 2019). According to the reports, each ton of OPC production results in the emission of 0.73–0.85 tons of CO_2 into the Earth's atmosphere (Shanks et al., 2019; Soltanzadeh et al., 2018).

In order to substantially reduce the release of carbon and other greenhouse gases, it is essential to implement sustainable and environmentally friendly replacements for cement production, such as a geopolymer or non-carbonate substance. In this case, the partial replacement of (OPC) with an alternative binder is mussel shell ash (MSA). Several studies showed that mussel shell waste exhibits a chemical composition similar to that of limestone, a key ingredient in manufacturing Portland limestone cement (PLC) (Maglad et al., 2023; Soltanzadeh et al., 2018). It comprises a $CaCO_3$ content of over 90% and is referred to as a CaO source when burned to grind into a powdery form. Therefore, mussel shells have the potential to serve as viable substitutes for limestone in the manufacturing of cement (Soltanzadeh et al., 2018; Ubachukwu & Okafor, 2019; Wang et al., 2019).

Furthermore, it ensures the use of aquaculture waste effectively and reduces the energy consumed in cement production. Additionally, MSA is only occasionally used in the construction industry. The study's fundamental purpose is to analyze the behavior and performance of concrete integrating MSA at various proportions ranging from 0% to 30%, and to promote waste material utilization for a sustainable future. The strength qualities were compared to those of the traditional NSC. In addition, the environmental impact of the LFC produced was examined.

2. METHODOLOGY

2.1 Materials

Ordinary Portland Cement (OPC) was used as the primary binder for preparing the concrete mixer as per BS EN 196-1:2016 (ASTM, 2013). Along with OPC, Mussel Shell Ash (MSA) was employed as the replacement of cement in quantities ranging from 0% to 30% due to its cementous properties. The cement replacement material, Mussel Shell Ash (MSA), was obtained from local fishermen. The shells were cleaned, cooked, and dried in an oven at 220°C for 1 hour. The dried shells were then ground into a powder with a particle size similar to OPC. The MSA has a high CaO content (94.6%) and similar chemical properties to OPC. The fine aggregate contained fine river sand with a maximum particle size of 4.75 mm.

Table 1: Chemical composition of OPC and Mussel Shell Ash

Material	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	SO_3	P_2O_5	MbO_3	LOI
OPC	19.01	4.68	66.89	0.81	0.09	1.17	3.20	3.66	0.08	2.48	4.68
MSA	0.55	0.03	87.21	0.49	0.050	0.04	0.05	-	0.09	-	-

2.2 Sample Preparation

The traditional low-cost foam sealant was derived from protein. It took roughly 10 minutes for it to dry, during which time the moisture and humidity in the air caused it to swell and solidify. After diluting the foam solutions with water in a 1:32 ratio, it can reach a of 65 ± 10 kg/m^3 density.

The dry elements were well combined using a drum mixer, according to table 2. After that, water was added little by little while being stirred continuously until a consistent mortar slurry was formed. The preliminary density of the mortar was measured by weighing the mortar slurry in a one-liter cylindrical container. The density of the foam was then determined, and the acceptable range was between 65 to 75 kg/m^3. The foam generator was used to generate the stable foam. To attain the desired density, a preset volume of foam was finally added to the mortar slurry. In order to generate LFC, the foam composition was regulated, the wet density was adjusted to a range of 1910 ± 40 kg/m^3, and the dry density was kept constant at 1750 ± 40 kg/m^3. A specific sand-to-cement proportion of 1.5:1 and a water-to-cement ratio of 0.48 were also implemented.

After that, steel molds were filled with the LFC mixture. After being allowed to cure for 48 hours, the LFC specimens were taken out of the molds, and their densities were then calculated. Subsequently, the LFC specimens were immersed in a water tank to initiate the curing process, which persisted until the day of the experiment. 24 hours before the planned testing day, the specimens were taken out of the water tank and dried in an electrically heated oven set to 105 °C. The aforementioned method was followed for 24 hours, or until a stable weight was reached.

Table 2: Mix Design of concrete

Mix ID	**Target density (kg/m^3)**	**Cement Replacement (%)**	**Additive (kg/m^3)**	**Cement (kg/m^3)**	**Sand (kg m^3)**	**Water (kg/m^3)**	**Foam (kg/m^3)**
MSA0	1750	0	0	639. 0	958. 5	306. 7	7.21
MSA5	1750	5	32	607.1	958.5	306.7	7.21
MSA10	1750	10	63.9	575.1	958.5	306.7	7.21
MSA15	1750	15	95.9	543.2	958.5	306.7	7.21
MSA20	1750	20	127.8	511.2	958.5	306.7	7.21
MSA25	1750	25	159.8	479.3	958.5	306.7	7.21
MSA30	1750	30	191.7	447.3	958.5	306.7	7.21

2.3 Property Analysis

The experimental methodology for this study involves analysing the cost-benefit analysis of MSA-based LFC as well as its mechanical qualities and environmental sustainability-

2.3.1 Mechanical Property Test

The physical characteristics of LFC were evaluated through three distinct types of tests: flexural, split tensile, and compression tests. After 7 and 28 days, the flexural test was conducted using a prism measuring 100 × 100 × 500 mm, in accordance with the standards outlined in BS12390-5. Subsequently, a cylinder with dimensions ∅ 100 × 200 mm was employed for the split tensile test, following the guidelines of BS12390-6 at both 7 and 28 days. The compression test utilized a cube measuring 100 × 100 mm, adhering to the specifications in BS12390-3. The LFC specimens were subjected to average flexural, split tensile, and compressive strength measurements at each specified age (Choong Kog, 2019; EN, 2009; Standard, 2009).

2.3.2 Sustainability

The environmental sustainability of MSA-based LFC will focus on three key aspects: eco-strength efficiency, CO_2 emission, and global warming potential (GWP).

2.3.2.1 Eco-strength efficiency

The eco-strength efficiency of mussel shell-based LFC is determined by comparing its compressive strength with its environmental impact. This efficiency metric is calculated as the ratio of embodied energy to compressible strength. Embodied energy encompasses the total energy required for the creation of a material, incorporating energy expended during extraction, transportation, processing, and manufacturing. Damineli et al. (2010) termed this CO_2 intensity, representing the amount of CO_2 emissions produced per unit performance. Alternatively, Alnahhal et al. (2018) referred to this concept as eco-strength efficiency. The MSA-based LFC specimens with a replacement MSA content will be created, and their compressive strength will be tested to determine the eco-strength efficiency. An assessment will be used to determine each specimen's embodied energy.

2.3.2.2 CO_2 Emission

To illustrate the effect of MSA on LFC's overall embedded CO_2 emissions, this study estimates the total CO_2 emissions by accounting for the equivalent CO_2 releases for each material. The data, which are shown in Table 3 format, were taken from related research studies.

Table 3: CO_2 emissions data for concrete.

Materials	Cement	Mussel Shell	Sand	Water	Foam
Total CO_2 emission (Kg CO_2 eq./kg material)	0.821	0.002	0.0139	0.000196	0.527
Reference	(Flower & Sanjayan, 2007)	(Soltanzadeh et al., 2021)	(Turner & Collins, 2013)	(Yang et al., 2013)	(Jhatial et al., 2021)

2.3.2.3 GWP

The GWP measures the potential contribution of greenhouse gases to global warming. The GWP assessment will account for greenhouse gas emissions, such as CO_2, during the MSA-based LFC's manufacturing and usage stages. The amount of each ingredient required to make one cubic meter of concrete was multiplied by the embodied CO_2 of each material, according to Table 4, to determine the embodied GWP for each concrete combination. The results were summed up then.

Table 4: Quantification of the environmental impact

Material	Cement	Mussel Shell	Sand	Water	Foam
individual GWP (kg CO_2-eq/kg material)	0.927	0.068	0.002	0	0.3
Reference	(Soltanzadeh et al., 2021)	(Soltanzadeh et al., 2021)	(Kua, 2013)		

2.3.3 Cost Efficiency

The benefits of employing MSA in relation to the cost of production per cubic meter of concrete were assessed in this investigation. Table [5] provides a full cost analysis of the individual materials used in the production and transportation phases. Market values were acquired for each component from its relevant supplier, such as "NEOTECH Construction Ltd." for admixture and "Seven Ring Cement" for Portland cement. Bangladesh's national water pricing at the time of computation was the basis for determining the price for mixing water. Sand and aggregate from Mongla were purchased at cost from neighborhood vendors, and mussel shells were purchased at a price reduction from neighborhood fishermen. A light vehicle conveyance was used to move mussel shells, and the transportation cost was estimated, considering fuel depletion rates and existing transportation statistics. The whole cost analysis was carried out utilizing Bangladesh-specific BDT exchange rates. MSA offers an option to manage polluted materials and waste disposal by replacing ordinary cement. Moreover, adding mussel shells to cement improves its mechanical qualities. These techniques significantly affect society by promoting a toxic-free atmosphere and space conservation.

Table 5: Production and transportation cost of the materials

Materials	Production cost (BDT/kg)	Transportation cost (BDT/kg)
Cement	11.4	1.15
Sand	1.78	0.4
Mussel shell ash	45	2.5
Water	0.098	-
Admixture	120	7
Foam	130	9

3. RESULT AND DISCUSSION

3.1 Mechanical Properties

3.1.1 Compressive Strength

Figure 1 illustrates a graphical depiction of the strength development over time about age for the control specimen, as well as the concretes containing varying percentages of Mussel shell ash. All combinations that were 7 days old exhibited a strength that surpassed the desired strength at 28 days by a minimum of 65%. Among all the mixtures, it was observed that the MSA15 specimen displayed the maximum compressive strength. In this case, the compressive strength of LFC was seen to reach 104.14%, 109.66%, 112.41%, 102.76%, 90.34%, and 82.76% of the control mix for MSA5, MSA10, MSA15, MSA20, MSA25, and MSA30, respectively, after 28 days. A comparable increasing pattern of MSA replacement, reaching a maximum of 20%, was likewise observed in the context of the compressive strength of the LFC after 7 days.

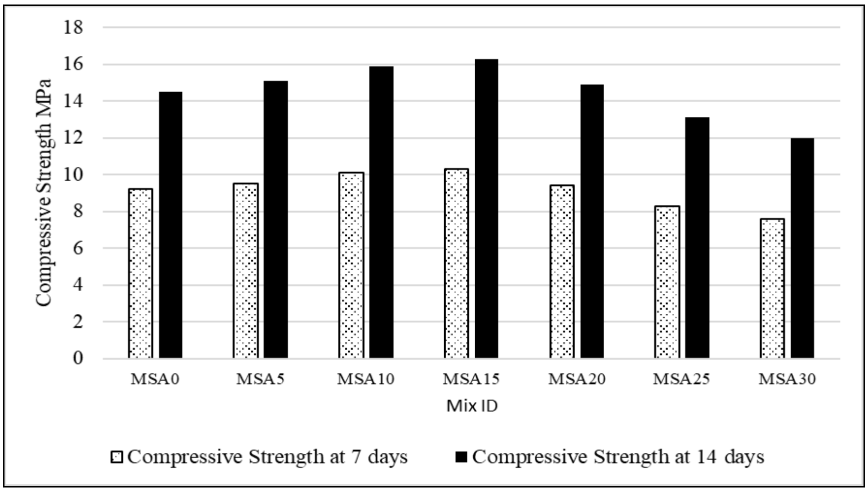

Figure 1: Compressive Strength of MSA concrete

However, the enhancement of strength mainly relies on the reaction between the higher concentration of silica in MSA and Ca $(OH)_2$, in combination with the hydration rate of OPC. The addition of 20% by weight of cement replacement in MSA enhanced the compressive strength of concrete, as MSA shows pozzolanic activity. According to the findings, an increase in the substitution of cement with mussel shell ash (MSA) leads to a rise in the compressive strength of mussel shell concretes, attributed to the pozzolanic reactions of MSA. This investigation observed that when the MSA replacement rates exceeded the specified thresholds, there was a noticeable decrease in compressive strength. Additionally, the observed decline in initial hydration can be explained by the presence of calcium oxide (CaO) in the MSA powder. This compound has the ability to react with aluminum oxide (Al_2O_3) and gypsum, resulting in a decrease in the previously mentioned reaction (Olivia et al., 2017).

3.1.2 Flexural Strength

Fig. 2. shows the graphical representation of the flexural strength, related to the time, of the control specimen with the different percentages of MSA-based concretes was seen in Among all the mixtures, it was observed that the MSA15 mix demonstrated the maximum flexural strength. In the case, the flexural strength of LFC was found to be 106.42%, 111.73%, 115.89%, 104.69%, 92.38%, and 86.80% of the flexural strength of the control mix for MSA replacement levels of 5%, 10%, 15%, 20%, 25%, and 30% correspondingly, at a curing period of 28 days. Additionally, Figure 2 shows a similar pattern in the flexural strength at a 7-day interval was noticed. Upon performing an analysis of the normalized flexural strength of concrete, it was found that the flexural strength of MSA-based concrete surpassed that of the control mix. This can be related to the higher binding characteristics of seashell cement with aggregates and the presence of fibers in the seashell ash concrete.

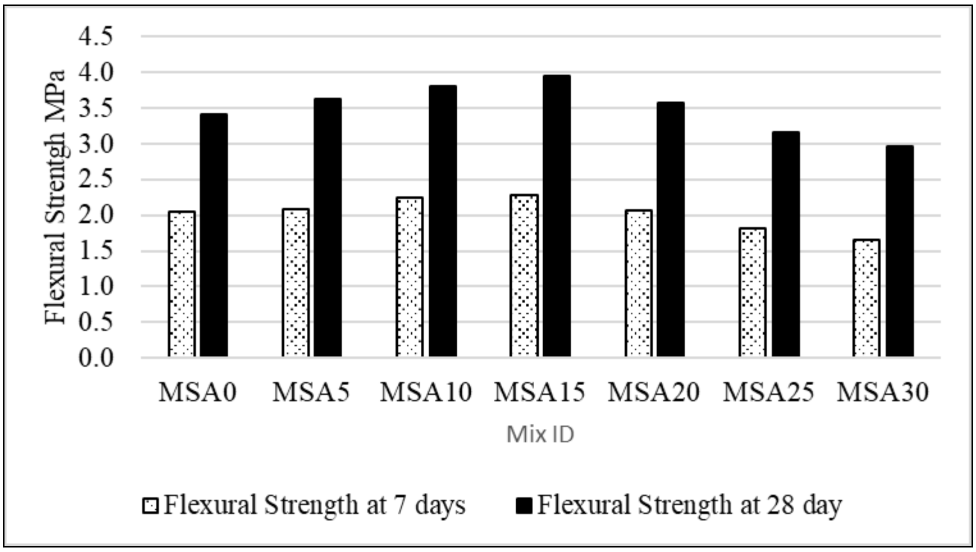

Figure 2: Flexural strength of MSA specimen

Also, seashell cement functions as a supplementary material that enhances the cohesive properties of concrete by strengthening the interparticle bonding. The use of seashell ash as a cement replacement at a weight percentage of 20% in MSA was observed to boost the flexural strength of concrete despite the rather gradual pozzolanic reactivity exhibited by the ash. The enhancement and interaction of the substance during the hydration process contribute to the strength level it attains before yielding to bending (Okoro & Oyebisi, 2023; Rollakanti et al., 2021). The grade of bonding and hardening achieved is determined by material responsiveness and the amount of oxide formation. Also, the presence of a higher concentration of CaO in mussel shells has been found to improve the adhesion at the interface between aggregates and cement paste (Olivia et al., 2015). When the replacement rate of mussel shell ash exceeded the predetermined levels, a related decrease in flexural strength was observed, indicating the interfacial bond between the cement paste and aggregates was disrupted to a greater extent as the replacement percentage increased. Sangeetha et al. (2022) reported similar results, indicating a decrease in flexural strength with an increasing percentage of seashell powder replacing cement.

3.1.3 Split Tensile Strength

The graphical representation of the split tensile strength at 7 and 28 days was found for the control specimen and for the concrete specimens with varying percentages of MSA-based seashell ash replacements. Among all the mixes, it was found that the MSA15 mix had the maximum tensile strength. At 28 days, the split-tensile strength of MSA-based ash concrete with different percentages of MSA replacement obtained 108.97%, 114.06%, 117.95%, 106.41%, 94.87%, and 88.46% of the tensile strength of the control mix, respectively. Figure 3 shows the same trend in the tensile strength at the 7-day periods for the MSA-based LFC. After conducting an analysis of the normalised tensile strength of concrete, it was found that the utilisation of MSA-based concrete resulted in higher tensile strength when compared to OPC. An equivalent improvement of concrete made using MSA ash was also reported by (Cuadrado-Rica et al., 2016). The incorporation of seashell ash (MSA) as a cement replacement at a weight percentage of 20% has been seen to enhance the splitting strength of concrete, despite the rather gradual pozzolanic activity exhibited by MSA. When the rates of MSA replacement above these levels, a concurrent decrease in splitting tensile strength was observed (Tayeh et al., 2020). A decrease in tensile strength was observed with the increase in ash replacement after incorporating 10% mussel shell ash powder. The utilisation of MSA powder in concrete mixtures results in a higher water absorption capacity compared to OPC. Consequently, the heterogeneous water absorption capacity of the various constituents in the concrete mix also reduces the splitting tensile strength. In addition, Olivia et al. (2017) discovered that including powdered cockle and clam shells as a substitute for 4% of the cement resulted in an enhancement in tensile strength in the concrete specimens compared to the typical cement concrete samples.

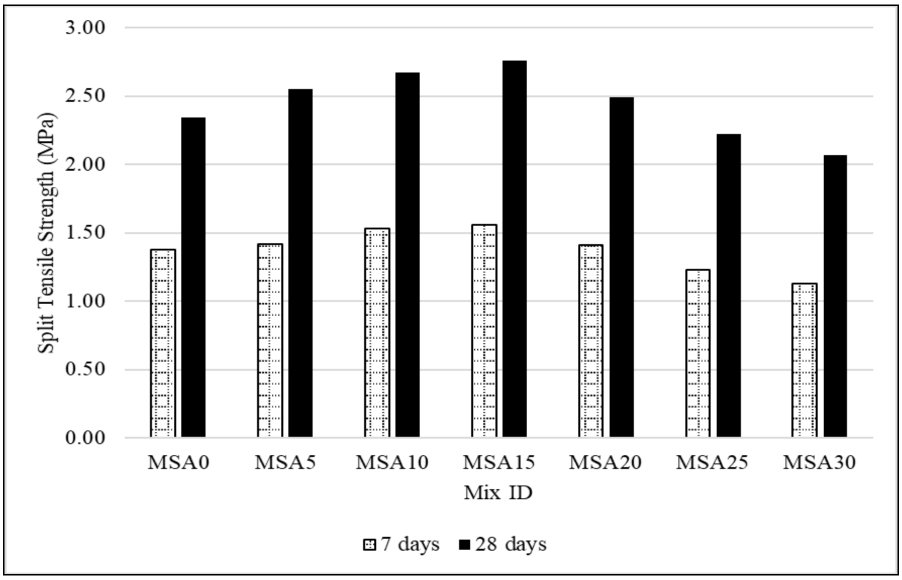

Figure 3: Split tensile strength

3.2 Sustainability

3.2.1 CO_2 Emission and GWP

The manufacturing of cement contributes to approximately 10% of global carbon dioxide emissions (Kumar et al., 2021). Concrete, the most extensively utilized construction material globally, possesses a significant carbon footprint due to the processes associated with raw material preparation. OPC, as the main binding element in concrete, accounts for approximately 75% to 90% of the total CO_2 emissions generated by concrete (Kumar et al., 2021).

Substituting 30% of the ordinary Portland Cement (OPC) with MSA significantly reduced CO_2 emissions. The CO_2 contribution of MSA0 input decreased from 541.8019 to 461.4796 kg-CO_2/m^3 for the MSA30 mix. This reduction is mainly due to the replacement of OPC with MSA.

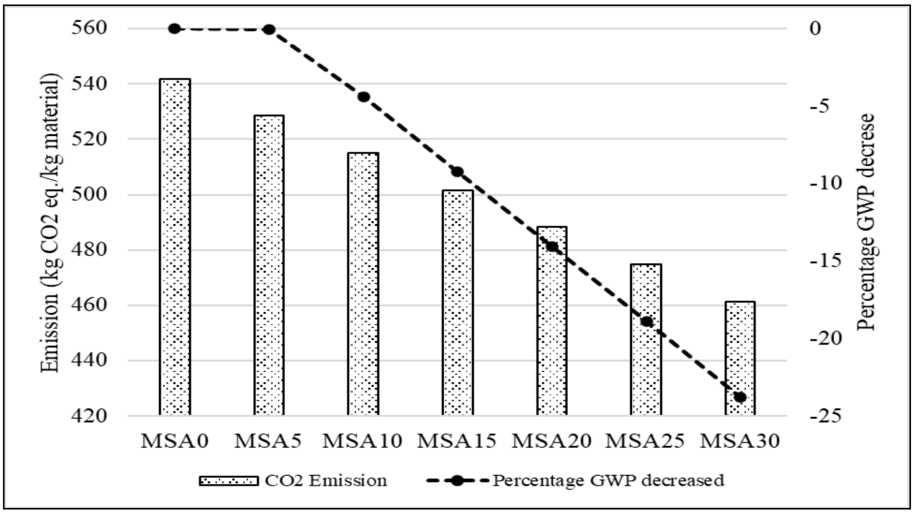

Figure 4: Total CO_2 Emission and GWP Enhancement Percentage

As the replacement of OPC increased by MSA powder, the emission of CO_2 decreased gradually. The impact can be vividly observed in the decreasing curve of GWP.

3.2.2 Eco-strength efficiency

When MSA is used in place of cement, CO_2 intensity can be decreased for a given strength, especially in later ages. When Portland cement was reduced from MSA0 to MSA15, for example, the CO_2 intensity decreased from 58.89151 MPa/kg CO_2-eq.m^{-3} to 48.7089 MPa/kg CO_2-eq.m^{-3} and increased from MSA15 to MSA30.

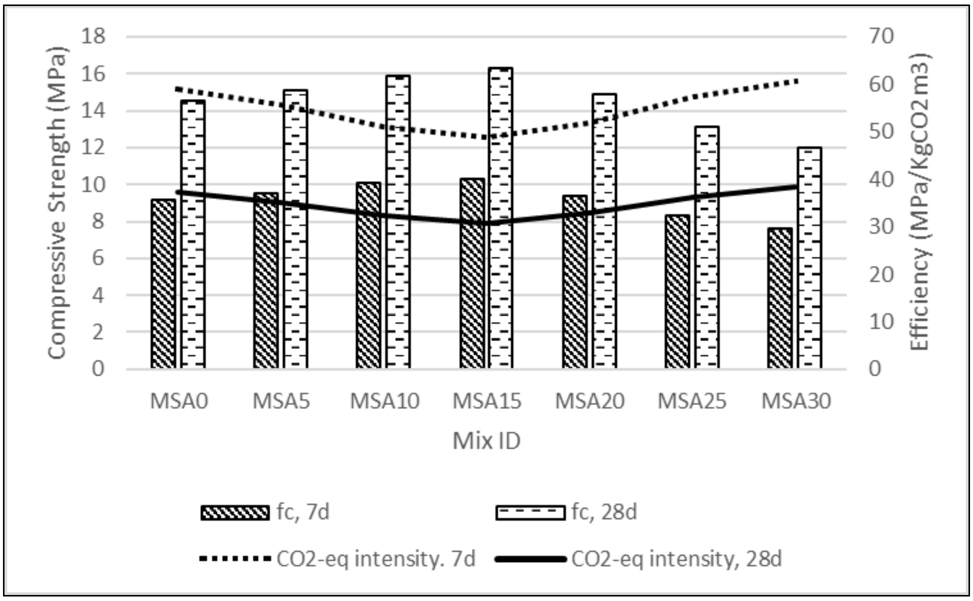

Figure 5: Eco-strength efficiency with respect to compressive strength.

3.3 Cost Efficiency

At BDT 11144 Tk per m^3 of concrete produced for the MSA0 mix, which consecutively decreased to the lowest total cost, BDT 8832 TK for the MSA30 mix. This is around 20.75% less expensive than the control mixture. Figure 6 shows the gradual reduction in cost with the replacement of cement.

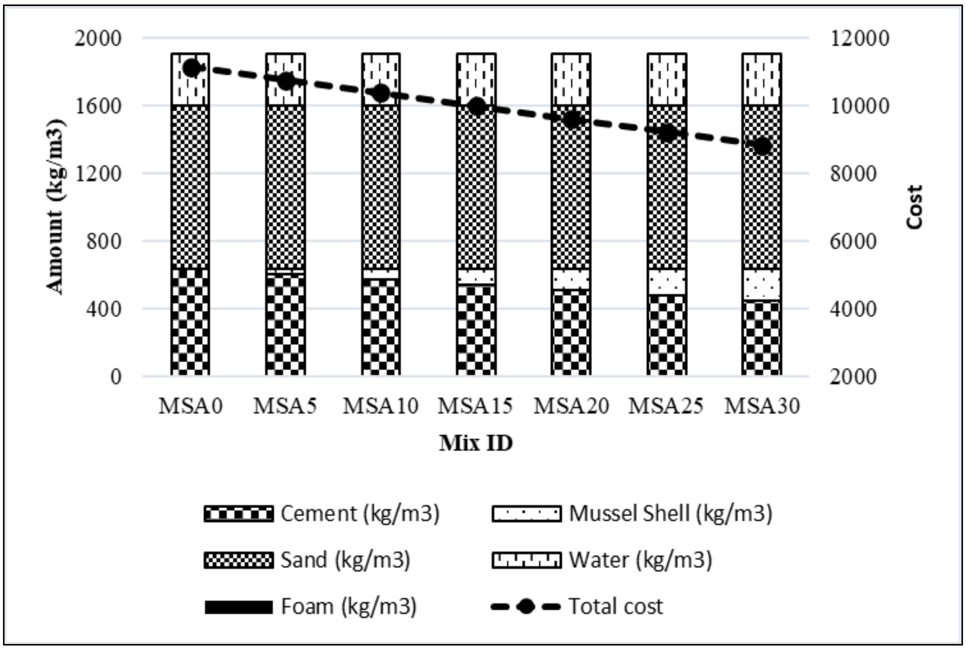

Figure 6: Cost efficiency

4. CONCLUSIONS:

The study offers an overview of the mechanical, environmental, and cost-benefit characteristics of the LFC in the detailed properties and makes the following conclusions:

- Comparing the 15% MSA replacement in LFC to the control mix, it was found that the improvements in flexural, split-tensile, and compressive strength were 15.89%, 17.95%, and 12.41%, respectively. The improvement is the highest value in each test compared to the other combinations.
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- The MSA30 mix showed the lowest GWP of 431.76 kgCO_2-eq/kg material, with a 23.77% reduction compared to the control mix. In contrast, the MSA15 mix showed a 9.23% GWP reduction while outperforming the control mix in compressive strength by 11.96%, indicating a noteworthy eco-strength efficiency.
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- Based on a cost-benefit analysis, the MSA30 mix was estimated to be roughly 20.75% less expensive than the control mix, resulting in the lowest overall cost. Despite this, the MSA15 mix only reduced costs by 10.38% when compared to the control mix.

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