Chapter 7
Eco-efficiency and Cost Index

7.1 Introduction

The preceding chapter offered in-depth insights into the structural, durability, and thermal characteristics of concrete when incorporated with MK and NS. In the ongoing investigation of MK and NS ternary concrete, the current chapter examines the eco-efficiency and economic efficiency of these blended cement concretes. Both eco-efficiency and economic efficiency play pivotal roles in optimising the replacement proportions of MK and NS, forming essential aspects for sustainable development. The eco-efficiency evaluation revolves around key metrics such as the binder intensity index (Bi) and CO_2 intensity index (Ci), providing a comprehensive understanding of the sustainability profile of MKNS blended concrete. Concurrently, economic efficiency is evaluated using the economy index derived from the concrete compressive strength. This is particularly significant as compressive strength serves as the primary criterion governing the structural performance of concrete.

7.2 Assessment of eco-efficiency

The eco-efficiency evaluation of concrete compositions was carried out based on Bi and Ci values, as outlined by Damineli et al. [321]. The Bi values represent the weight of binder (kg) required to produce one m^3 of concrete to achieve a single unit of performance. Given the significant apprehension about global warming within the concrete industry, creating an indicator facilitating the comparison of concrete formulations based on their CO_2 emissions becomes crucial. Damineli et al. also suggested using CO_2 intensity (Ci), characterised as the amount of CO_2 released to achieve one unit of performance. Therefore, the Bi and Ci values can be calculated regarding compressive strength, carbonation, acid resistance, etc.

In assessing eco-efficiency for mechanical and durability performances, this study focuses on deriving Bi and Ci values specifically for compressive strength, denoted as Bi_{CS} and Ci_{CS}. Additionally, the evaluation of the eco-efficiency pertaining to the durability performance of concrete mixes involves the consideration of Bi and Ci values related to carbonations, represented as Bi_{CARB} and Ci_{CARB}

7.2.1 Eco-efficiency for mechanical performance

The lowest values of Bi and Ci define the eco-efficiency for the mechanical performance as assessed below. The eco-efficiency of the concrete mixes for compressive strength, the principal mechanical property of the concrete, was evaluated as follows.

i ***Binder intensity for compressive strength***

The Bi_{cs} is calculated as the total consumption of binder material (kg/m^3) to deliver 1 MPa of strength. Therefore;

$$B_i = \frac{B}{CS} \qquad \text{Equation 7.1}$$

B is the total amount of binder material(s) used to produce 1m^3 of concrete, and CS is compressive strength at the desired curing age. 450 kg of binder materials, such as cement, MK, and NS, was utilised to produce concrete specimens of each composition. Table 7.1 illustrates the Bi_{CS} values of concretes for compressive strength at 28, 90, and

180 days. A reduced binder intensity for compressive strength indicates superior efficiency in achieving the necessary strength.

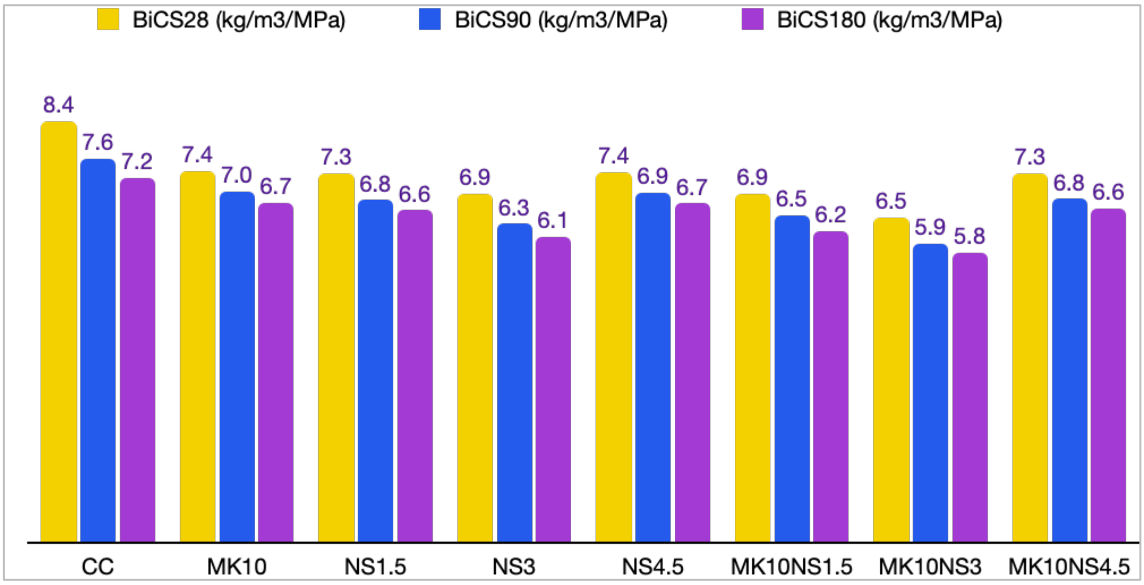

Figure 7.1 Binder intensities of concrete for 28, 90 and 180-day compressive strength

There was a discernible downward trend in the Bi_{CS} values as the compressive strength increased. The MK10NS3 concrete formulation had the lowest Bi_{CS} values, demonstrating a remarkable eco-efficient profile. Specifically, it recorded 6.5, 5.9, and 5.8 kg m^{-3} MPa^{-1} values for compressive strength at 28, 90, and 180 days, respectively. In contrast, ordinary concrete with OPC showcased higher values, reaching 8.4, 7.6, and 7.2 kg m^{-3} MPa^{-1} for strength at 28, 90, and 180 days, respectively. Notably, a consistent decline in Bi_{CS} values was observed as the curing ages increased.

The study aligns with Damineli et al.'s perspective, considering Bics values nearing 5 kg m^{-3} MPa^{-1} as eco-efficient. Remarkably, only the MK10NS3 composition approached these eco-efficient Bi_{cs} values, specifically at 90 and 180 days, with values of 5.9 and 5.8.

Consequently, the lower Bi values of MK10NS3 establish it as the most efficient concrete composition in terms of compressive strength.

ii ***CO_2 intensity for compressive strength***

The CO_2 intensity for compressive strength (Ci_{CS}) is the amount of CO_2 emitted to achieve 1 MPa compressive strength. Therefore;

$$C_{ics} = \frac{c}{cs} \qquad \text{Equation 7.2}$$

Where 'C' represents the total amount of CO_2 (kg/m^3) released during concrete production. The CO_2 emission for aggregates and transportation were not considered in the study. The CO_2 emission per unit weight of OPC ($CO_{2\text{-}OPC}$) was taken as 0.9 kg based on data supplied by Ultratech Cement Ltd., a cement manufacturing company. Additionally, the CO_2 emission per unit weight of MK ($CO_{2\text{-}MK}$) was taken as 0.236 kg, as reported by Maddalena et al. in 2018 [322], and the CO_2 emission for NS ($CO_{2\text{-}NS}$) was considered negligible, as the NS particles are synthesised by chemical process.

Table 7.1 Binder content and the CO_2 emission of the concrete mixes

Mix	OPC (kg/m^3)	MK (kg/m^3)	nS (kg/m^3)	CO_2 emission (kg/m^3)
CC	450.00	0.00	0.00	405.00
MK10	405.00	45.00	0.00	374.85
NS1.5	443.25	0.00	6.75	398.93
NS3	436.50	0.00	13.50	392.85
NS4.5	429.75	0.00	20.25	386.78
MK!0NS1.5	398.25	45.00	6.75	368.78
MK10NS3	391.50	45.00	13.50	362.70
MK10NS4.5	384.75	45.00	20.25	356.63
$CO_{2\text{-}OPC}$ = 0.9 kg/m^3, $CO_{2\text{-}MK}$= 0.236 kg/m^3, $CO_{2\text{-}nS}$= 0 kg/m^3				

The CO_2 emission per one m^3 of concrete was calculated from the weight of the binder(s) used to produce each concrete. The binder content of each concrete composition and their respective CO_2 emissions are given in Table 7.1.

The CO_2 emission for each concrete can thus be calculated from the following expression.

$$CO_{2\text{-concrete}} = \text{Weight of Binder x } CO_{2\text{-binder}} \text{ ,or} \qquad \text{Equation 7.3}$$

Therefore, the '*C*' in the *Equation 3* becomes,

$$C = OPCxCO_{2\text{-OPC}} + MKxCO_{2\text{-MK}} + NSxCO_{2\text{-nS}} \qquad \text{Equation 7.4}$$

The CO_2 intensities for the compressive strength of the concretes at 28, 90 and 180 days are calculated from Equations 7-3 and 7-4 and are given in Figure 7.2.

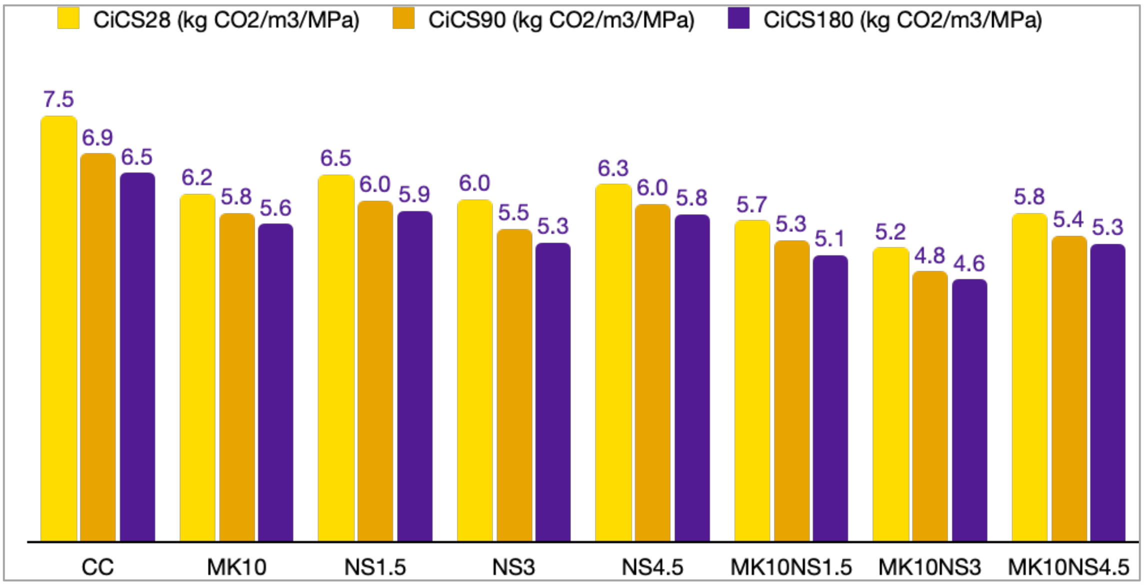

Figure 7.2. CO_2 intensities of the concrete for 28, 90 and 180-day compressive strength

The MK10NS3 concrete attained the lowest Ci_{CS} values, measuring 5.2, 4.8, and 4.6 kg CO_2 m^{-3} MPa^{-1} at 28, 90, and 180 days, respectively, signifying superior efficiency compared to other concrete blends. These values fall within the average Ci_{CS} values estimated for international data reported by Damineli et al. The heightened eco-efficiency of MK10NS3 can be attributed to its lower cement content and higher compressive strength. Notably, a discernible trend emerged, showcasing a reduction in Ci_{CS} as cement content decreased. All the ternary compositions exhibited lower Ci values, indicating that the lower cement content and high strength led to its superior performance to the normal concrete. The Ci values for normal concrete were notably higher, underscoring elevated CO_2 emissions attributable to the high OPC content.

7.2.2 Eco-efficiency for durability performance

Unlike in the eco-efficiency for mechanical strength, the highest values of Bi and Ci are defined as the eco-efficiency of concrete in terms of durability properties such as carbonation. The eco-efficiency of the concrete mixes for carbonation, a crucial durability parameter, was evaluated as follows.

i ***Binder intensity for carbonation***

The Bi of the concrete for carbonation represents the weight of the binder (kg/ m^3) for one unit of natural carbonation coefficient (k_{nat} in mm/√year).

$$B_i = \frac{B}{k_{nat}} \qquad \text{Equation 7.5}$$

The Bi_{CARB} values shown in Figure 7.3 illustrate the binder intensities of various concrete mixes. Notably, MK10NS3 exhibited the highest binder intensity, surpassing

MK10NS1.5 and NS3 compositions. In contrast, normal concrete displayed the lowest binder intensity among the tested formulations. The heightened binder intensities observed in the ternary concrete mixes, especially at 10% MK and 3% NS proportions, suggest that these combinations are environmentally efficient, primarily attributed to their reduced cement contents.

ii ***CO_2 intensity for carbonation***

The CO_2 intensity for the carbonation is calculated the same way as it was for compressive strength. Therefore,

$$C_{iCARB} = \frac{C}{k_{nat}} \qquad \text{Equation 7.6}$$

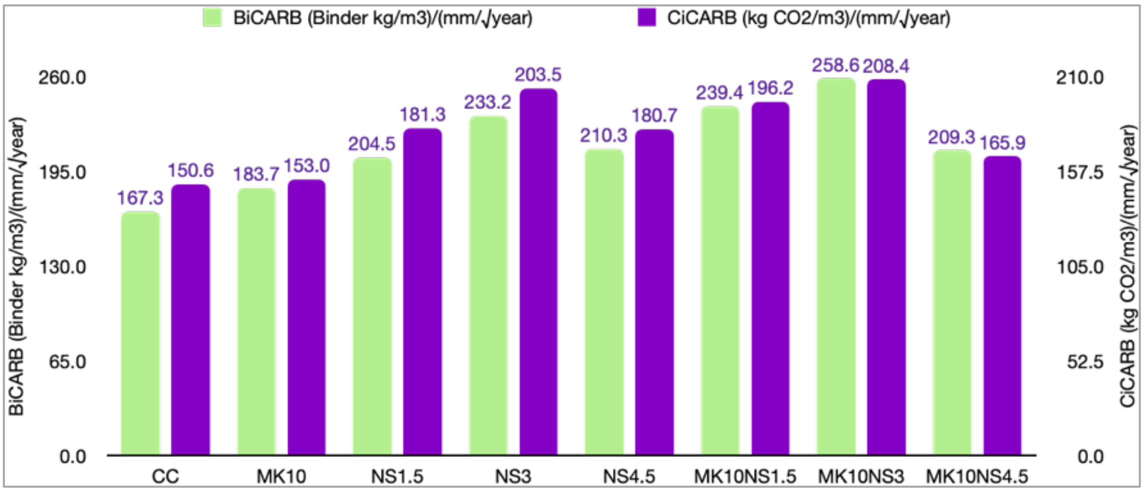

Figure 7.3. Binder and CO_2 intensities of concrete for carbonation

Figure 7.3 shows the obtained results for the Ci_{CARB}. Regarding carbonation resistance (k_{nat} mm/√year), MK10NS3 exhibited a higher Ci, followed by NS3 and MK10NS1.5. In NS3, a slightly elevated Ci value, compared to MK10NS1.5, can be ascribed to the variations in the proportional relationship between CO_2 emissions and k_{nat} observed in NS3 and MK10NS1.5.

7.3 Cost index

The cost index was derived by calculating the cost of producing individual concrete mixes, including transportation and procurement costs. The cost index was determined as the ratio between the 28-day compressive strength of the concrete and the production cost per cubic meter of concrete [323]. Table 7.2 presents the concrete cost per cubic meter and the corresponding cost indices for the various concrete mixes.

Table 7.2 reveals that, except for NS 4.5 and MK10NS4.5, the cost indices for binary and ternary mixes of MK and NS closely align with that of normal concrete CC. Despite the elevated cost associated with blended concrete, its superior strength compared to CC offsets the higher production expenses. A higher cost index signifies the optimal mix proportion from an economic standpoint.

Table 7.2. Cost index of concrete

Mix	28 day CS (MPa)	Cost/m³ (₹)	Cost index
CC	53.8	9844.00	0.0055
MK10	61.0	10679.00	0.0057
NS1.5	61.4	10992.00	0.0056
NS3	65.0	12468.00	0.0052
NS4.5	61.2	13672.00	0.0045
MK10NS1.5	64.9	11720.00	0.0055
MK10NS3	69.7	13086.00	0.0053
MK10NS4.5	61.4	14290.00	0.0043
Cost index = 28 day CS/ Cost per m³			

MK10 yielded the highest cost index at 0.0057, indicating its greater economic viability than normal concrete CC with a cost index of 0.0055. Similarly, NS1.5 exhibited a higher cost index than CC, whereas MK10NS1.5 demonstrated an equivalent cost index to CC. MK10NS3, boasting the highest compressive strength, featured a cost index of 0.0053, closely approximating that of CC, thereby establishing its economic viability. Conversely, NS4.5 and MK10NS4.5 exhibited the lowest cost index values, rendering them economically inefficient despite possessing a compressive strength higher than CC.

7.4 Summary

The lower Bi_{CS} and Ci_{CS} values and the higher Bi_{CARB} and Ci_{CARB} values of MK10NS3 compositions suggest its higher eco-efficiency. MK10NS3 exhibited impressive Bics values of 6.5, 5.9, and 5.8 kg m^{-3} MPa^{-1} at 28, 90, and 180 days, meeting eco-efficient criteria proposed by Damineli et al. The lowest Ci_{CS} values at 5.2, 4.8, and 4.6 kg CO_2 kg m^{-3} MPa^{-1} for MK10NS3 signify superior efficiency compared to other blends, falling within the average Ci_{CS} values reported internationally. Despite slightly increased production expenses, the cost index analysis revealed the economic viability of MK10NS3 composition, closely approximating the cost index of normal concrete CC. These findings highlight MK10NS3 as sustainable and economically feasible.

Economic efficiency is closely associated with the durability of the concrete. Concrete structures with increased durability require less frequent maintenance, repair, and replacement, reducing life-cycle costs. Reduced maintenance expenses and longer service life contribute to economic savings over the long term, making durable concrete economically efficient. Moreover, the upfront investment in high-quality, durable materials pays off by minimising future expenditures, making it a cost-effective and financially prudent choice. The study showed that MKNS ternary blends performed well in carbonation, water absorption and acid resistance, underscoring their durability compared to the other concrete compositions, particularly to the normal concrete. Therefore, the enhanced durability of MKNS, particularly at their respective 10% and 3%, not only aligns with the sustainability goals by reducing environmental impact but also proves economically efficient by optimising life-cycle cost and resource utilisation.