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RESEARCH ARTICLE

Investigating embodied carbon, mechanical properties, and durability of high-performance concrete using ternary and quaternary blends of metakaolin, nano-silica, and fly ash

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Abstract
Research for alternative binders has become a necessity due to cement's embodied carbon, climate change, and depletion of natural resources. These binders could potentially reduce our reliance on cement as the sole binder for concrete while simultaneously enhancing the functional characteristics of concrete. Theoretically, the use of finer particles in the cement matrix densifies the pore structure of concrete and results in improved properties. To validate this hypothesis, current research was designed to investigate how the value-added benefits of nano-silica (NS) and metakaolin (MK) in fly ash (FA)-blended cement affect the mechanical and durability characteristics of concrete when used as ternary and quaternary blends. Additionally, the cost–benefit analysis and environmental impact assessment were conducted. It was observed that the synergy of MK and NS used in FA-blended cement had a greater impact on enhancing the functional characteristics of concrete, while 10% MK as ordinary Portland cement (OPC) replacement and 1% NS as an additive in FA-blended OPC concrete was the optimum combination which achieved 94-MPa compressive strength at the age of 91 days and showed more than 25% increment in the flexural and splitting tensile strengths compared to the control mix (MS00). The ultrasonic pulse velocity and dynamic modulus of elasticity were significantly improved, while a significant reduction in chloride migration of 50% was observed. In terms of environmental impact, MS100 (30% FA and 10% MK) exhibited the least embodied CO_2 emissions of 319.89 $kgCO_2/m^3$, while the highest eco-strength efficiency of 0.268 $MPa/kgCO_2 \cdot m^{-3}$ with respect to 28-day compressive strength was exhibited by MS101. In terms of cost–benefit, MS00 was determined the cheapest, while the addition of MK and NS increased the cost. The lowest cost of producing 1 MPa was exhibited by MS01 with a merely 0.04-$/MPa/$m^3$ reduction compared to MS00.

Keywords Cost–benefit analysis · Durability · Embodied carbon · Mechanical properties · Metakaolin · Nano-silica · Ternary blending · Quaternary blends

Introduction

Ordinary Portland cement (OPC) based concrete is used in every structural application, and it is suitable for normal construction projects. Generally, concrete structures have to withstand harsh environmental conditions such as structures subjected to waterlogging and salinity and structures exposed to chloride environments such as a marine environment that

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result in damage to concrete structures (Shafiq et al. 2019). One of the primary reasons for durability failure is corrosion, and the most common source of corrosion is the aggression of chloride ions into the concrete which affects strength loss, long-term performance, and esthetic appearance of reinforced concrete structures (Bagheri and Zanganeh 2012). Thus, in recent years, it has gained increasing attention because of its extensive occurrence (Song et al. 2008). The concrete industry contributes to emissions of carbon dioxide (CO_2) into the environment between 5 and 7% globally due to the production of cement and its use in concrete (Benhelal et al. 2013). The emission of CO_2 in the production of cement is a major concern for the environment. Xi et al. (2016) estimated that for the period of 1930 to 2013, 76.2 billion tonnes of cement were produced and consumed, subsequently releasing 38.2 billion tonnes of CO_2 gas into the atmosphere. According to a recent report from US Geological Survey (2019), approximately 4.1 billion tonnes of cement were produced in 2018 alone. To produce 1 tonne of cement, approximately 0.9 tonne of CO_2 gas is emitted (Maddalena et al. 2018) and also consumes 1.5 tonnes of raw materials (Rashad 2015). With the expectation that in coming years, the demand for concrete will increase and, therefore, so will the production of cement. It has caused alarms due to its contribution to climate change as well as the depletion of natural resources.

The production of high-strength and high-performance concrete (HPC) requires lower water-binder (w/b) ratio in combination with special admixtures (Bharatkumar et al. 2001). However, the reduction in water content results in lower lubrication and flowability among binder particles and may leave unfilled air voids in a mix (Abd Elrahman and Hillemeier 2014; Kwan and Wong 2008). In the construction sector, researchers are exploring to identify several techniques to improve the durability and sustainability concerns related to building materials. During the last decade, nanomaterials have received extensive attention in the construction industry to achieve the exceptional performance of materials and sustainable features (Li et al. 2019; Li et al. 2018; Sikora et al. 2020). One of the nanomaterials which are widely used in concrete for its pozzolanic activity and pore-filling effect is nano-silica (NS). The combination of nanomaterials with agro/industrial waste materials into the concrete has become the most common way to improve the serviceability of structures (Li et al. 2019; Zareei et al. 2019). It is beneficial because it improves the refinement of the pore structure of concrete, which results in less permeability and higher strength (Kumar et al. 2017). Many supplementary cementitious materials (SCMs) are available that can be used in concrete. The most established are fly ash (FA), metakaolin (MK), silica fume, and so on (Valipour et al. 2013). There are two most commonly, MK and silica fume, used pozzolans in construction projects. The performance of both pozzolans is almost identical with a similar replacement level for enhancing the compressive strength and decreasing the permeability of concrete (Kumar et al. 2017). In the past two decades, there has been growing interest among concrete researchers in the use of MK as a partial cement replacing materials for the production of concrete with improved mechanical and durability characteristics (El-Din et al. 2017; Sabir et al. 2001; Salimi et al. 2020; Ženíšek et al. 2016).

Lenka and Panda (2017) investigated 10% replacement for MK in concrete for enhancement in compressive strength. Similar findings have also been observed by other researchers (Dinakar and Manu 2014; Parande et al. 2008; Wild et al. 1996). The use of such materials in higher proportions leads to a reduction in water absorption and chloride permeability. The addition of NS particles in concrete has shown enhancement in compressive strength than control concrete (concrete produced with 100% of cement) up to 6% (Berra et al. 2012; Said et al. 2012). The binary effect of MK and FA was investigated at different replacement levels by Sujjavanich et al. (2017). It was reported that a denser microstructure can be achieved with a mix proportion consisting of 10% substitution of MK and FA, respectively, by weight of the total binder. Enhanced durability was also exhibited by the mix. Different academic scholars have utilized different dosages of NS to identify its effects on concrete properties. Berra et al. (2012) concluded that no considerable development in the compressive strength was achieved for cementitious mixes with the addition of NS. Jalal et al. (2015) who investigated mechanical, thermal transport, and microstructure of concrete utilizing 2% of NS along with silica fume and FA.

Based on the literature review, it is identified that most researchers have investigated and reported the effects of binary blending using MK, FA, or NS (Ghafari et al. 2014; Güneyisi et al. 2014; Islam 2011). However, there is inadequate research available that investigates the enhancement in strength- and durability-related properties of concrete using ternary and quaternary blends of MK and NA in fly ash-blended cement. This research aims to investigate the effect of multiple blending to improve the properties of concrete.

Research significance

Ever since its inception, concrete has been the most widely preferred and considered durable among building and construction materials. However, during its service life, concrete structures may be damaged due to being subjected to various environmental exposures, improper design, management, and poor material durability (Kumar et al. 2017; Shafiq et al. 2019). It is expected that the concrete structures should be serviceable for several years without showing any damages or deformations. To enhance the concrete properties, the use of mineral admixtures and nanomaterials is considered as a promising method acclaimed by various scholars

(Flores-Vivian et al. 2013; Nazari and Riahi 2011). Recently, more focus has developed on the utilization of different pozzolanic materials in binary and ternary blends to improve the functional characteristics of concrete. However, the effect of quaternary blends of MK, NS, and FA on strength and durability properties is not widely explored and is still novel. Additionally, there exist limited study on the environmental impact of the ternary and quaternary binders on the total CO_2 emissions of concrete, however, as per authors knowledge, there is no study on the environmental impact on the total CO_2 emissions of concrete when MK, NS and FA are used simultaneously in concrete. Therefore, this study focuses on the effectiveness of multiple blending in enhancing the properties of high-performance concrete and the environmental impact assessment.

Research methodology

Materials

The OPC used in this research was CEM I which complies with the requirements of BS-EN 197-1. It was obtained from Tasek Cement Limited Berhad, Ipoh, Malaysia. The specific surface area and specific gravity of OPC were 1.06 m^2/g and 3.15, respectively. MK used in this study was prepared from kaolin clay which was obtained from Ipoh, Malaysia. Previously, MK has been produced in different ways by different researchers, i.e., incinerating kaolin at 800°C for 1 h (Ramezanianpour and Bahrami 2012; Saikia et al. 2006), 2 h (Liew et al. 2012), 3 h (Wang et al. 2012), and 6 h (Zhang et al. 2012). However, for the current study, MK was prepared by incinerating kaolin clay at 800°C temperature for 3 h, following the recommendations of Shafiq et al. (2015), in which it was found that incinerating kaolin clay at 800°C for 3 h is the optimum condition. The surface area of MK was found to be 11.44 m^2/g using Brunauer–Emmet–Teller (BET) analysis. The specific gravity of MK was 2.50. The FA used in this study was obtained from a local source, Manjung Power Station in Perak, Malaysia. The sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ was determined to be 72.7%, and the LOI was 5.1; based on the criteria suggested by ASTM C618-19 (2019), FA can be characterized as class F fly ash. The surface area and specific gravity of FA were found to be 1.08 m^2/g and 2.38, respectively. NS used in this research was obtained from China. The average particle size of NS used in this research was obtained in the range of 10–25 nm. The specific surface area was found to be 100 ± 25 m^2/g. The chemical compositions of all binding/replacement materials is presented in Table 1, which were obtained using the X-ray fluorescence (XRF) technique.

Crushed granite as a coarse aggregate (CA) with a maximum size of 14 mm was used in this study. It was obtained from Papan Granite, Ipoh, Malaysia. The specific gravity and the water absorption of CA were 2.62 and 1.24%, respectively, while the fineness modulus was 4.5. The mining sand, supplied by a local supplier in Tronoh Malaysia, was used as fine aggregate. Aggregate passing from a 4.75-mm sieve was used in concrete. The specific gravity and water absorption of sand were 2.63 and 1.04%, respectively, while fineness modulus was 2.74. The superplasticizer (SP) was used along with a constant w/b ratio of 0.35 for all mixes to keep the workability in the range of 100–130 mm.

Mix design and casting

The experiment was designed using design expert software. The details of the mix design are shown in Table 2. The desired strength of 80 ± 5 MPa was obtained after performing several trials, as there is no standard method to design a higher compressive strength mixture. The final mix proportions for the HPC mixes contained 0–10% MK and 0–2% NS. The labels were assigned to prominently illustrate the parameters and their proportion in the concrete mix, i.e., MS00; "M" signifies metakaolin, followed by "S" that represents the nano-silica along with the respective percentage in the mix. The first digit indicates the % of MK while the last digit indicates the % of NS.

To avoid the agglomeration and uniform desperation of NS, the materials were dry mixed in an automatic mixer to achieve the uniform dispersion of nanoparticles with MK and cement. The ingredients were mixed in order of aggregates, FA-blended OPC, MK, and NS. The aggregates were mixed individually for 1 min followed by a 3-min mix with half of the FA-blended OPC, NS, and MK. The remaining portions of

Table 1 Chemical composition of binders

Chemical composition (%)								Physical properties	
Constituents	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	SO_3	LOI	BET surface area (m^2/g)	Specific gravity
OPC	62.85	4.59	25.21	1.70	2.99	-	2	1.06	3.15
FA	18.0	14.0	35.80	2.66	22.90	1.11	5.1	1.08	2.38
MK	0.58	35.1	53.3	0.27	2.73	0.14	7.4	11.44	2.50

Table 2 Mix proportions

Mix ID	Factors		kg for 1-m^3 concrete							SP	Slump
	MK (%)	NS (%)	Cement	FA	MK	NS	Sand	CA	Water	(%)	Mm
MS00	0	0	350	150	0	0	735	990	175	0.40	120
MS01	0	1	350	150	0	5	736	990	175	0.70	115
MS02	0	2	350	150	0	10	735	990	175	0.85	118
MS50	5	0	325	150	25	0	735	990	175	0.55	103
MS100	10	0	300	150	50	0	735	990	175	0.75	105
MS51	5	1	325	150	25	5	735	990	175	0.90	117
MS52	5	2	325	150	25	10	735	990	175	1.05	115
MS101	10	1	300	150	50	5	735	990	175	1.00	120
MS102	10	2	300	150	50	10	735	990	175	1.10	121

materials were added into the mixer and left for mixing for an additional 2 min. Then the required amount of water with SP was slowly added, and the mix was given some more blending time to form a homogenous mixture. The fresh concrete was discharged, and the slump test was immediately performed. Moulds were prepared by pouring the freshly mixed concrete into three layers and compacted on the vibration table, and an even surface was obtained by surface finishing in the end. Upon the completion of moulding, the samples were left for 24 h at room temperature, after which, the specimens were unmoulded and placed in water for curing until the desired testing period.

Experimental procedure and testing

The mechanical performance of the concrete samples was assessed by compressive strength, tensile strength, flexural strength, ultrasonic pulse velocity (UPV), and dynamic modulus of elasticity. The compressive strength test was executed following BS EN 12390-3 (2019) at 3, 7, 28, and 91 days. The strength was recorded on a 100-mm cube specimens at the loading pace of 3 kN/s using the 3000-kN compression testing machine. The splitting tensile strength test was executed on 100-mm diameter and 200-mm-long cylindrical samples at the age of 28 days in accordance with the requirements of BS EN 12390-6 (2009). In addition, the UPV test was performed at the age of 28 days, complying with ASTM C597 (2016), on the same cylinders before it was used for the splitting tensile test. Using the UPV values obtained from the UPV test, the dynamic modulus of elasticity was calculated for all the mixtures using Eq. (1). A flexural strength test was performed at the age of 28 days according to BS EN 12390-5 (2019) on a 100 × 100 × 500-mm-long prism.

$$E_D = (UPV)^2 \left[\frac{\rho(1+\mu)(1-2\mu)}{(1-\mu)} \right] \quad (1)$$

where, ρ is the unit weight in kg/m^3 on the 28th day and μ is the dynamic Poisson ratio. The value of μ was assumed to be 0.2 (Lamond and Pielert 2006). The durability characteristics were measured by investigating the specimen for its resistance against chloride migration and water absorption tests. For chloride migration, a rapid chloride permeability test (RCPT) and an immersion test for measuring chloride penetration depth were performed. The test was performed complying with ASTM C1202-19 (2019); the total charge passed is an indication of chloride permeability of concrete (ASTM C1202-19 (2019)). At the end of the RCPT test, the $AgNO_3$ solution is sprayed over two halves to measure the depth of penetration.

Results and discussion

Compressive strength

The variations in compressive strength with respect to MK and NS are shown in Fig. 1. An addition of 1% NS with an FA-blended OPC showed an increase in compressive strength at all curing ages. The addition of 1% NS presented a strength of 81 MPa at 28 days, and the strength continued to increase up to 86 MPa at 90 days. Incorporation of NS beyond 2% presented a slight decline in strength up to 5% at different curing ages. The reduction is accredited to the agglomeration of NS particles in the cement matrix. The NS particles demand sufficient water due to the higher surface area to complete the hydration and dispersion of nanoparticles. Thus, the unreacted or partially reacted particles of NS are accumulated at one point in the matrix, which results in the formation of larger pores and causes a reduction in strength.

Substitution of MK in proportions, i.e., 5% and 10%, as replacement of cement caused a significant increase in strength than control mix (MS00). An increase of 5% and 2% in the strength was seen with respect to the control mix

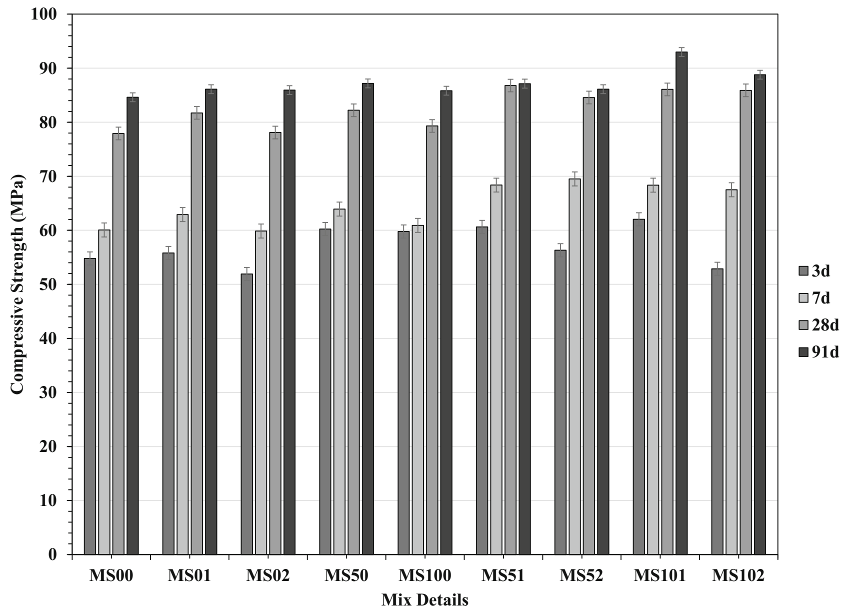

Fig. 1 Compressive strength variation containing MK and NS in FA-blended cement

(MS00) at 7 days and 28 days, respectively. Overall, the increment was recorded in the range of 3 to 9% in all percentages of MK with respect to its control mix (MS00). Rao and Maruthi (2016) and Stefanidou and Papayianni (2012) also reported similar findings in their research. The finer materials act as activators and increase the reactivity of pozzolanic materials, enhancing the hydration process and rate of strength development (Zhuang and Chen 2019). Past studies (Baioumy and Ibrahim 2012; Mardani-Aghabaglou et al. 2014) showed that MK has positive influence on the concrete's strength due to two reasons: the filler effect and secondary calcium silicate hydrate (C-S-H) development. Substitution of 10% MK with cement showed a slight decline in strength with the corresponding mix (MS50), but the strength was observed to be higher than the control mix (MS00). The approximated reduction of 3% was quantified at the age of 7 and 28 days, respectively. The reduction in early strength is mainly because of the slow pozzolanic activity of the FA. The synergy of MK and NS presented higher strength values at all curing ages. A concrete mix containing 10% MK with 1% NS presented higher compressive strength than other concrete mixes studied in this research. The addition of 2% NS with 5% MK showed significant improvement compared to the control mix (MS00); however, a slight decline in compressive strength was observed compared to its respective mix (MS51). The approximate increase using 5–10% MK with 1% NS blends was recorded between 10 and 12% at 28 days of curing with respect to the control mix. Overall, it was observed that the NS had greater compatibility to develop the concrete with higher compressive strength.

Tensile and flexural strengths

Figure 2 illustrates the variation in splitting tensile strength containing MK and NS in FA-blended OPC at 28 days of curing. All concrete mixes containing MK and NS exhibited higher tensile strength compared to the control mix (MS00). This is accredited to the particle packing of the cementitious matrix due to the formation of additional C-S-H. An addition of NS mix presented similar or exceeded strength to the control mix (MS00). The strength was increased by 5% and 0.5% with the addition of 1% and 2% NS, respectively, compared to the control mix (MS00). Similar to the compressive strength, 2% NS showed a slight decline in the strength than the corresponding mix (MS01) but slightly higher than the control mix (MS00).

Overall, the ternary and quaternary blended mixes showed improved flexural strength than the control mix (MS00). The addition of 1% NS with ternary blended OPC (containing FA and MK) produced a 7% and 18% increment in the flexural strength than mix MS50 and MS100, respectively. This strength was 22% and 28% higher than the control mix (MS00). The addition of NS beyond 1% showed a decline in the flexural strength than the corresponding mix (MS51 and MS101), but this was much higher than the control mix. This shows the value-added benefits of using NS in improving the strength parameters of concrete. The substitution of MK also provided greater enhancement in the flexural strength of concrete samples. Overall, 25% and 12% higher strength were recorded using 5% and 10% MK, respectively, as a substitution for OPC. While 10% and 5% increments were recorded using 1% and 2% NS in the concrete specimen, respectively.

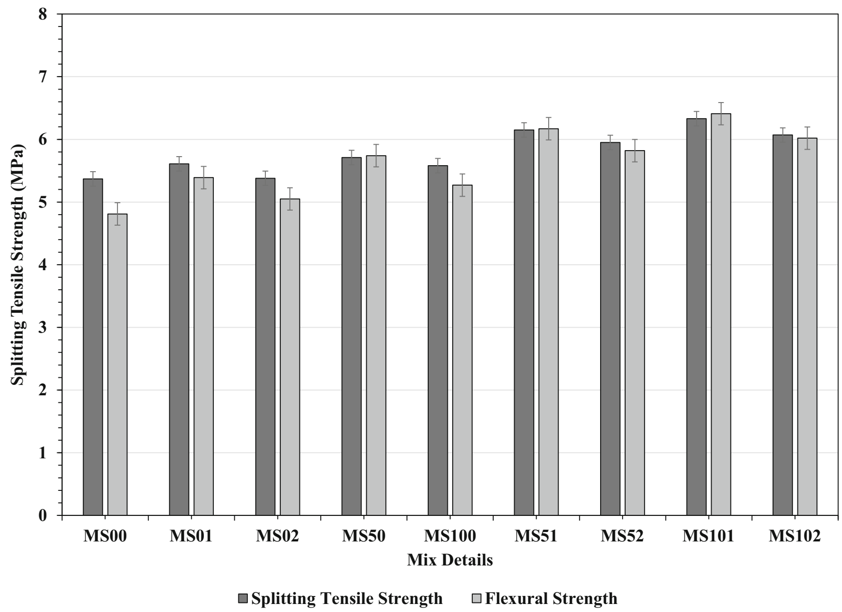

Fig. 2 Behavior of tensile and flexural strengths containing MK and NS in FA-blended cement

Ultrasonic pulse velocity (UPV)

The UPV test is a non-destructive method for measuring the strength of concrete samples. This test was performed at 28 days on a cylindrical specimen using an ultrasonic tester. Figure 3 demonstrates the behavior of UPV values on ternary and quaternary blended binders containing MK and NS with FA-blended OPC. The quality of concrete corresponding to UPV values can be quantified using the following criteria suggested by ASTM C597 (2016): UPV > 4000 m/s is assumed to be good concrete, 4000 m/s > UPV > 3000 m/s is moderate concrete, and UPV < 3000 m/s is considered to be poor concrete.

It is evident from Fig. 3 that the mix containing MK and/or NS shows higher velocity values than the control mix (MS00). Overall, the UPV values were recorded above 4000 m/s for all specimens in the category of fairly good concrete. The control mix (MS00) also performed better in the control concrete (MS00). A similar trend in the case of FA was also reported by Ahad et al. (2019). Among the quaternary blended specimen containing MK and NS with FA-blended OPC, the mix (MS52) showed slightly lower UPV values than other samples. A mix containing 10% MK with 1% NS presented a higher UPV value than the rest of the concrete mixes. The increment was recorded by 4.5% and 3% higher than the control mix (MS00) and respective mix (MS100), respectively.

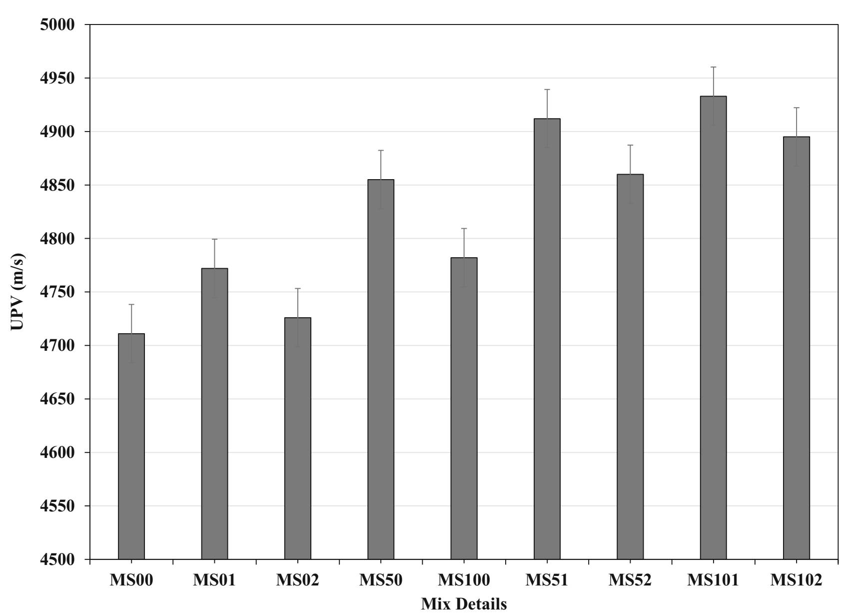

Fig. 3 Behavior of UPV values containing MK and NS in FA-blended cement

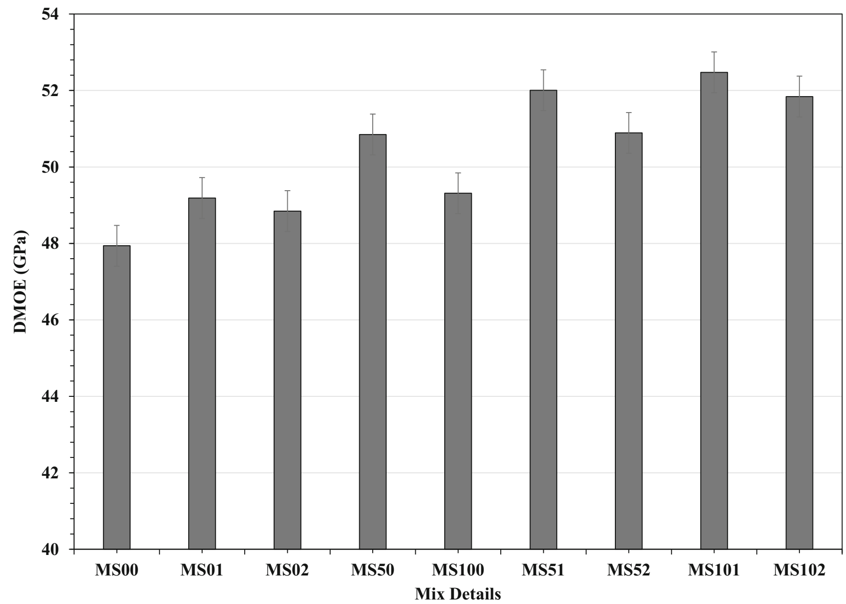

Fig. 4 Behavior of DMOE containing MK and NS in FA-blended cement

The increment is attributed to the same reason mentioned in "Compressive strength." The substitution of MK beyond 5% showed a slight decline in the UPV value. However, the addition of 1% NS with MK showed great improvement. The addition of NS beyond 1% showed an approximately 0.5% and 2% reduction in UPV values than the control mix and corresponding mix (MS01), respectively. The reduction is attributed to the agglomeration of nanoparticles into the cement matrix. In this phenomenon, the larger pores are formed due to the accumulation of nanoparticles at one point within the cement matrix.

Dynamic modulus of elasticity

The variation in dynamic modulus of elasticity (DMOE) values for all mixtures is shown in Fig. 4. The DMOE values increase with respect to MK and NS contents in the concrete mixtures. The magnitude of DMOE with the addition of 1% NS in the FA-blended OPC mix was an increase of 2.5% compared to the control mix (MS00). Furthermore, the addition of 2% NS presented a slight decline in the corresponding mix, but it increased by 2% than the control mix. This can be attributed to the non-uniform dispersion of NS particles within the cement matrix. The ternary blend of MK with FA-based OPC also presented higher DMOE values. The DMOE of concrete was increased by 2% and 1% using 5% and 10% MK, respectively. The combination of MK and NS showed an exceptional increment in the DMOE values. The blend of 10% MK and 1% NS showed 6% and 9% enhancement in the DMOE values with respect to the corresponding mix (MS100) and control mix (MS00), respectively. This is attributed to the higher pozzolanic reactivity of the materials.

Chloride permeability

All mixes studied in this research exhibited chloride penetration depth values in the "very low" range. Table 3 shows the value of the coulomb charge passed in 6 h for various concrete mixes. Figure 5 shows the graphical representation of chloride penetration depth values on concrete mixes prepared with MK and NS using FA-blended OPC. The values of passing charge corresponding to chloride penetration depth values for ternary and quaternary blended mix lie between 289–847 C and 2.98–6.00. The chloride ingress was reduced by 7% and 28% using 1% NS and 5% MK, respectively. However, their combination (MS51) exhibited a drastic decrease of 40%. Likewise, the combination of multiple proportions of NS with 10% MK presented a severe reduction in chloride penetration resistance compared to all mixes studied in this research. A decrease of 50% and 47% was observed using 1% and 2% NS, respectively.

The reduction can be attributed to the filler effect of MK and NS due to its pozzolanic reaction which creates additional C-S-H inside the matrix and densifies the microstructure of concrete. This can be due to the pore connectivity inside the concrete specimen. This is due to the chloride binding capacity of FA in concrete. The results obtained are in agreement with those reported previously in the literature (Mardani-Aghabaglou et al. 2014; Nath and Sarker 2013). The compatibility of MK and FA concretes achieved better resistance to chloride permeation than other combinations.

Water absorption

Figure 6 shows the individual and combined effects of MK, NS, and FA on water absorption at 28 days. It is obvious from

Table 3 RCPT test results

Mix	Penetration depth (mm)	Passing charge (Coulombs)	Class (ASTM C1202 - 19 (2019))
MS00	6.00	847	Very low
MS01	5.57	775	Very low
MS02	5.85	659	Very low
MS50	4.33	512	Very low
MS100	4.55	617	Very low
MS51	3.62	358	Very low
MS52	3.79	487	Very low
MS101	2.98	289	Very low
MS102	3.17	419	Very low

the results that the reduction in water absorption was observed at different time intervals with the replacement of OPC containing varying percentages of MK and 30% FA. For the control mix (MS00), the percentage weight increase of 3.74% was calculated at 28 days. However, the rest of the concrete mixes depicted the lower values. The combination of 10% of MK and 1% NS with 30% FA has shown the lowest values at 28 days in this series. Utilizing 1% and 2% NS with FA showed a 52% and 54% decrease in water absorption, respectively, than the control mix (MS00). A blend of FA and NS presented a great combination to improve the reduction in water absorption of concrete.

The water absorption results were analyzed together with compressive strength and chloride penetration depth. Generally, higher compressive strength is related to the reduction in water absorption (Khatib and Clay 2004). The same behavior is also seen in this research. Figure 7a shows a correlation between compressive strength and water absorption for all mixes. A strong correlation is obtained between the R^2 value of 0.91. Similarly, Fig. 7b also presents an excellent correlation between water absorption and chloride penetration depth, showing an R^2 value approximately similar to compressive strength. The R^2 value near to 1 shows the effectiveness of the model and statistically measures the closeness of data near to the regression line.

Environmental impact assessment

Production of cement contributes to roughly 10% of the total global CO_2 gas emissions (Benhelal et al. 2013; Suhendro 2014; Zhang et al. 2014). Concrete, which is the main building material being used worldwide, has a significant carbon footprint due to activities involved in the preparation of raw materials. Since the main binder material in the concrete is OPC, it contributes to between 74 and 81% of the total CO_2 emissions of concrete. The

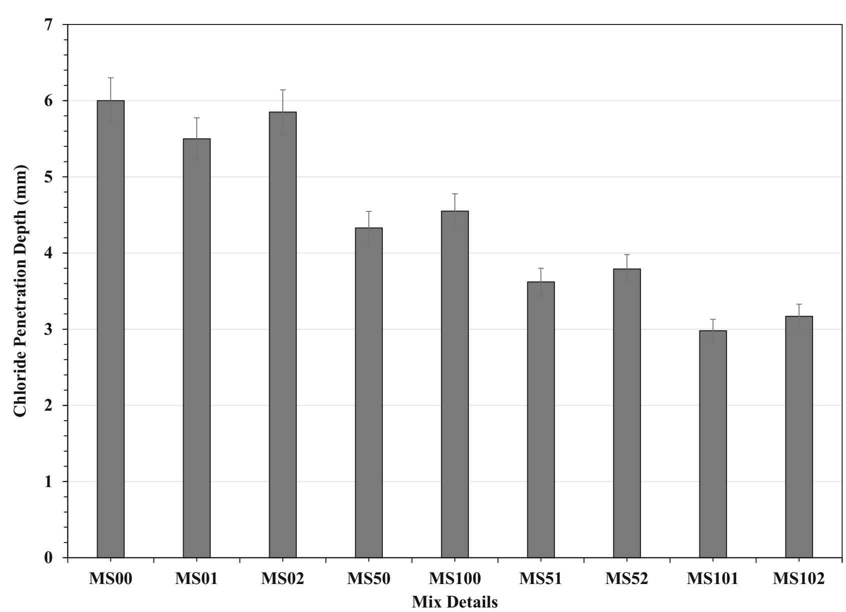

Fig. 5 Behavior of chloride penetration depth containing MK and NS in FA-blended cement

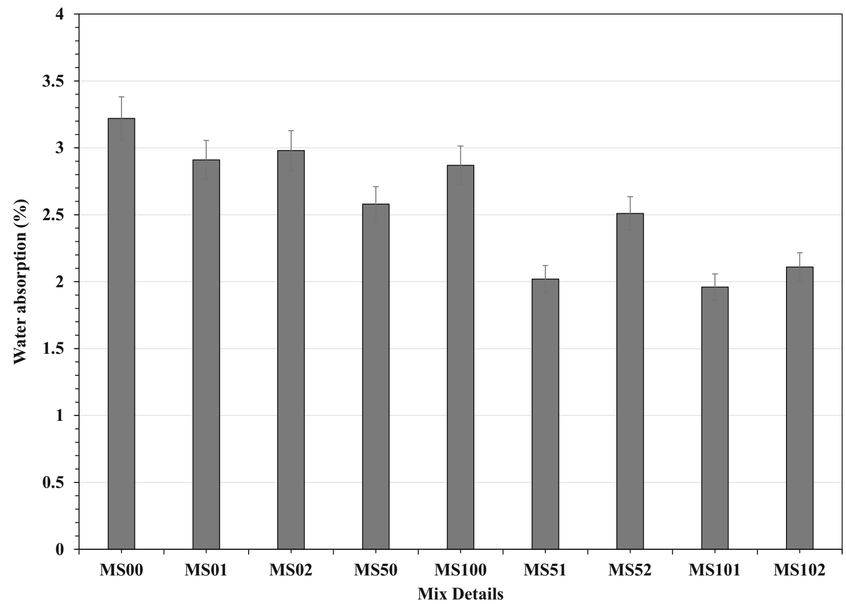

Fig. 6 Behavior of water absorption containing MK and NS in FA-blended cement

awareness regarding CO_2 emissions has allowed the development and/or use of alternative binder materials to cut down the dependency of OPC as the main binder in concrete. SCMs which include pozzolan materials have been widely used to partially substitute cement content. It is anticipated that significant reductions can be achieved with the utilization of such SCMs. This is due to the fact that

1. The SCMs are usually end products of manufacturing processes and are easily available, thus do not require extraction.
2. The overall energy used to prepare these SCMs is generally less.
3. The reuse of waste materials in concrete contributes towards sustainability, as it avoids dumping of such materials in landfills.

Though the utilization of SCMs will surely reduce the overall embodied CO_2 emissions of concrete; however, different waste materials will have different embodied CO_2 emissions. As for this current study, FA and MK were used as binder materials, along with NS used as additives. Their individual embodied CO_2 will contribute towards the total embodied CO_2 of concrete. Therefore, to demonstrate the influence of ternary and quaternary binders on the total embodied CO_2 emissions of HPC, the total CO_2 emissions are estimated in this study using the equivalent CO_2 emissions for each material. These values have been taken from recent literature and are shown in Table 4. Furthermore, for the sake of comparison, a reference concrete mix with a similar amount of materials and without the use of SCMs is taken from a previous study (Shafiq et al. 2019) and referred hereafter as CM.

The kg of CO_2 per kg of each material provided in Table 4 and the equivalent CO_2 emissions are considered as cradle to gate, which includes the production process, transportation, and mixing. The total embodied CO_2 values for each concrete mix were found by multiplying the weight of each material to produce 1-m^3 concrete with embodied CO_2 of each material

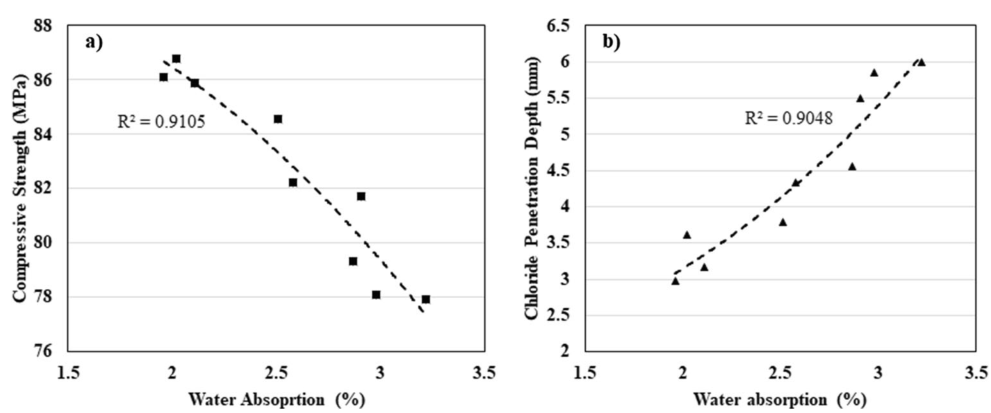

Fig. 7 Correlation of water absorption with **a** compressive strength and **b** chloride penetration depth

Table 4 Total CO_2 emissions emitted to produce 1-m^3 HPC concrete

Materials	$KgCO_2/kg$	Ref	CO_2 emissions for 1 m^3 of concrete ($kgCO_2/m^3$)									
			CM	MS00	MS01	MS02	MS50	MS100	MS51	MS52	MS1201	MS102
OPC	0.82	(Flower and Sanjayan 2007)	410	287	287	287	266	246	266.5	266.5	246	246
FA	0.027	(Turner and Collins 2013)	0.00	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05
MK	0.33	(Meddah et al. 2018)	0.00	0.00	0.00	0.00	8.25	16.50	8.25	8.25	16.50	16.50
NS	0.00084	(Adamu et al. 2018)	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01
Sand	0.0139	(Turner and Collins 2013)	10.22	10.22	10.23	10.22	10.22	10.22	10.22	10.22	10.22	10.22
CA	0.0408	(Turner and Collins 2013)	40.39	40.39	40.39	40.39	40.39	40.39	40.39	40.39	40.39	40.39
Water	0.000196	(Yang et al. 2013)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
SP	0.72	(Long et al. 2015)	1.80	1.44	2.52	3.06	1.98	2.70	3.24	3.78	3.60	3.96
Total			462.44	343.13	344.23	344.76	331.42	319.89	332.69	333.23	320.80	321.16

and then summing them together. As observed from Table 4, the OPC is the leading embodied CO_2 of concrete compared to other materials. For the CM mix, OPC accounts for approximately 88.66% of the total CO_2 emissions. This was reduced significantly by replacing 30% OPC with FA (MS00 mix). The OPC CO_2 contribution dropped from 410 to 287 $kgCO_2/m^3$, while FA only added 4.05 $kgCO_2/m^3$ to the total. Thus, MS00 was able to reduce 25.8% of CO_2 emissions. However, the reduction in OPC and utilization of FA had an adverse influence on the strength (a loss of 11.76%), as the reported 28 days strength of CM was 88.3 MPa while MS00 exhibited 77.92 MPa. However, the addition of MK and NS along with FA in concrete not only reduced the difference in strength but also reduced even further the embodied CO_2 emissions. The lowest embodied CO_2 emissions of 319.89 $kgCO_2/m^3$ were exhibited by MS100, in which a total of 40% OPC substitution was done (30% FA and 10% MK). In addition to the reduced CO_2 emissions, MS100 achieved slightly better strength than MS00 of 79.31 MPa, which is 10.18% lower than CM but 1.78% higher than MS100.

However, the least strength loss of 1.71% compared to CM was achieved by the MS51 mix (86.79 MPa). MS51 consisted of 30% FA and 5% MK as binders (total 35% OPC replacement) and the addition of NS as an additive. However, the embodied CO_2 emissions of MS51 were higher than MS100 but still 28.06% lower when compared to CM mix as shown in Fig. 8. The increase in embodied CO_2 emissions when compared to MS100 is due to the fact that lower OPC substitution was done and also, to achieve a roughly similar slump, a higher content of SP was used which subsequently added additional CO_2 emissions. The reduction in embodied carbon with the inclusion of SCMs observed in the current study agrees with previous studies (Alnahhal et al. 2018; Bheel et al. 2021; Jhatial et al. 2021).

Thus, it can be concluded that substituting OPC content with SCMs will certainly reduce the overall embodied CO_2 emissions. The higher the substitution of OPC with SCMs, the lower the total CO_2 emissions of the concrete mix will be. However, as observed in the current study, the higher the

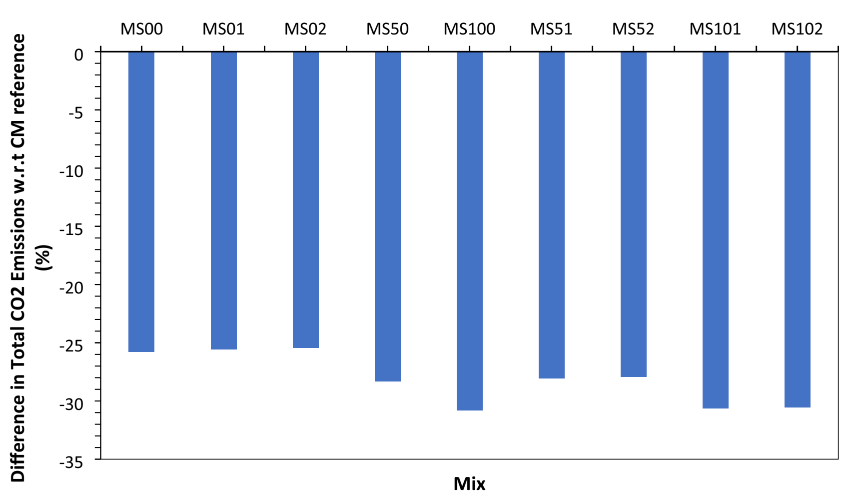

Fig. 8 Difference in embodied CO_2 emissions compared to reference CM mix

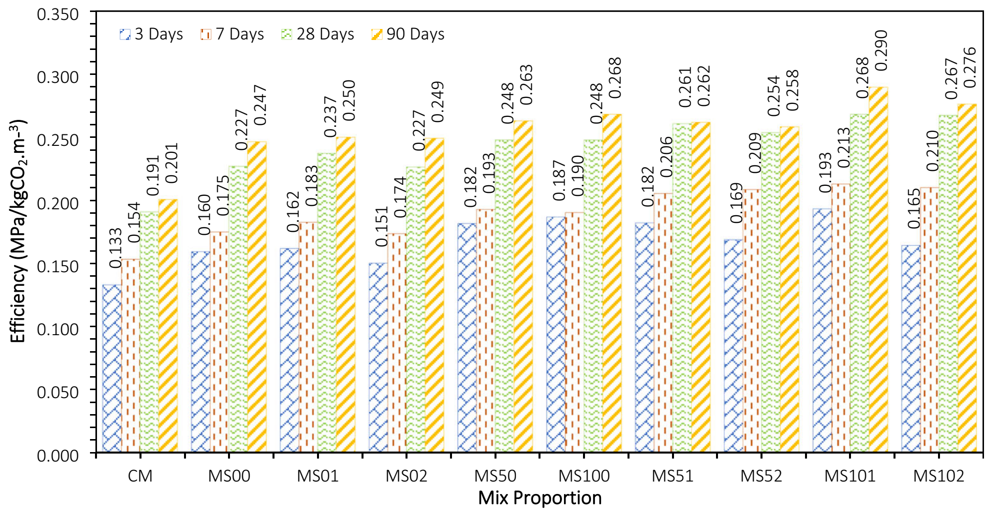

Fig. 9 Eco-strength efficiency of different mixes of HPC

substitution level of OPC, the lower strength will be. Therefore, not only does the reduction in CO_2 emissions matter but also strength.

The environmental impact assessment can also be evaluated by the eco-strength efficiency of concrete mixes. The eco-strength efficiency (Alnahhal et al. 2018) or the CO_2 intensity (*ci*) (Damineli et al. 2010) can be defined as the amount of CO_2 emissions which are released to produce one unit of performance. It is calculated by Eq. (2):

$$ci = \frac{CO_2}{c.s} \tag{2}$$

where *ci* is the CO_2 intensity or eco-strength efficiency, CO_2 is the embodied CO_2 emissions emitted by the concrete as calculated in Table 4, and *c.s* is the compressive strength. The current study calculates the eco-strength efficiency for the compressive strength of concrete achieved at different ages as shown in Fig. 9. For sake of comparison, the CM mix was taken from a previous study (Shafiq et al. 2019) and which achieved 61.67 MPa, 71.07 MPa, 88.3 MPa, and 92.88 MPa for 3-, 7-, 28-, and 91-day compressive strength, respectively.

The eco-strength efficiency of CM mix was determined to be 0.133 MPa/kgCO_2·m^{-3} at 3 days, increasing gradually over time, to 0.154, 0.191, and 0.201 MPa/kgCO_2·m^{-3} at 7, 28, and 90 days, respectively. The % increase was reduced as the concrete aged. As for MS00, MS01, MS02, MS50, MS100, and MS101, the difference in efficiency between 3 and 7 days was restricted between 0.3% and 2.3%. This may be due to the pozzolanic reaction caused by FA and MK, thus causing slow strength gain at an early age. As for MS51, MS52, MS101, and MS102, the difference in efficiency between 3 and 7 days was much higher at 2 to 4.5%. This higher difference can be attributed to the NS additive.

It can also be observed that a significant jump in efficiency is exhibited by all mixes except CM. This can be attributed to the gaining of strength due to the pozzolanic reaction. The highest eco-strength efficiency of 0.268 MPa/kgCO_2·m^{-3} with respect to 28-day compressive strength was exhibited by MS101. This was achieved due to MS101 exhibiting the second highest 28-day compressive strength among the mixes (not including CM), while emitting the second least CO_2 emissions. While the least CO_2 emitting concrete mix exhibited an eco-strength efficiency of 0.247 MPa/kgCO_2·m^{-3}.

Previous studies (Alnahhal et al. 2018; García-Segura et al. 2014; Jhatial et al. 2021) have also shown that the eco-strength efficiency increases with the increase in OPC substitution level. However, the efficiency will vary. According to Alnahhal et al. (2018), the maximum efficiency can be achieved by a 20% OPC replacement. As most SCMs have a higher specific surface area, thus absorbing more water will restrict workability. A further increase in OPC replacement beyond 20% will reduce the strength of concrete. However, in the current study, high-strength concrete is developed with the addition of SP, which improves workability and strength. Thus, the higher substitution can be made, without compromising much on the strength or eco-efficiency.

Cost–benefit analysis

In addition to the environmental impact assessment, the cost–benefit is also a vital factor that the construction industry considers before adopting any newer or blended concrete. The cost–benefit of ternary and quaternary binder concrete

Table 5 Local price of materials

Materials	OPC	FA	MK	NS	Sand	CA	Water	SP
Cost ($/kg)	0.095	0.025	0.58	0.095	0.025	0.045	0.001	1.2

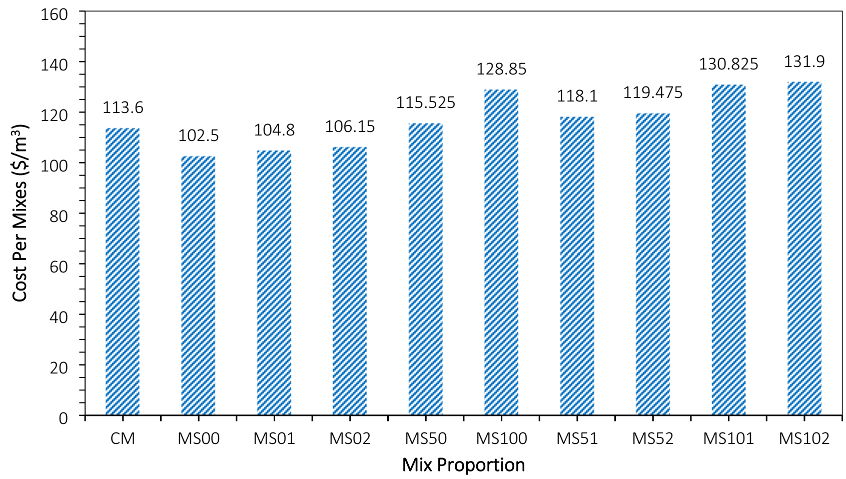

Fig. 10 Cost of 1 m^3 of HPC mixes

investigated in this study is calculated for each mix based on the local prices of each material. The rate of $ per kg of each material is shown in Table 5.

The prices of different materials are highly dependent on their local availability. The cost of FA, a pozzolanic material, is relatively lower than the price of OPC. While the cost of NS is relatively similar to that of OPC. However, MK is a relatively expensive pozzolanic material, as it is only extracted in a select number of countries. Therefore, the higher inclusion of MK and NS will definitely increase the overall cost of the concrete. The cost of each concrete mix per 1 m^3 is shown in Fig. 10. It can be observed that the CM mix costs \$113.6 per m^3 of concrete. The main contributors to the price are OPC and SP. The least cost is incurred by MS00, which is \$102.5 per m^3 of concrete. This is approximately 9.77% cheaper than CM. With the addition of 1% and 2% NS in MS01 and MS02, respectively, the cost of concrete increases slightly, but it is still lower than the cost of CM. Though the cost of NS and OPC is similar, the addition of NS causes a reduction in workability. Therefore, a higher dosage of SP is required to achieve near-similar workability. This higher dosage of SP contributes to increasing the overall cost. The incorporation of MK as a binder, due to its higher cost, increases the overall cost of concrete, much higher than the CM mix.

As observed from Fig. 10, the overall cost of each mix varies; however, a comprehensive cost–benefit analysis cannot be considered as complete without assessing the cost to produce 1 MPa of strength for each mix. Therefore, the cost to produce a 1-MPa compressive strength at 28 days is calculated and shown in Fig. 11. The lowest cost of producing 1 MPa was exhibited by MS01 with a merely 0.01-$/MPa/m^3$ reduction compared to CM and 0.04-$/MPa/m^3$ reduction compared to MS00.

Conclusion

This research work investigated the effects of ternary and quaternary blending on concrete strength and durability properties, as well as the cost–benefit and environmental impact

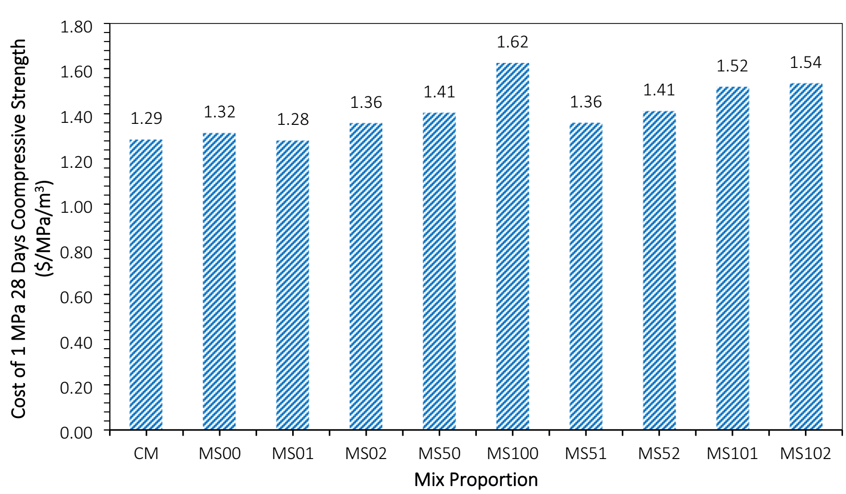

Fig. 11 Cost to produce 1-MPa compressive strength for each mix

assessments. Based upon the results obtained, it was observed that:

(1) Concrete mixes containing 10% MK content showed the highest compressive, flexural and tensile strengths at all curing ages. Whereas, 1% or 2% NS only did not show remarkable improvement when used separately. However, a significant enhancement was observed in combination with MK.
(2) The improvement was also recorded in the UPV and dynamic modulus of elasticity values. The overall enhancement in DMOE was observed by 6% when compared with control concrete.
(3) The resistance to chloride penetration and reduction in water absorption was significantly improved with the incorporation of MK and NS. The best combination of 1% NS with 10% MK has shown a drastic decrease of 50% in chloride penetration depth. Similarly, this combination resulted in the least water absorption and a smaller range of median pore diameter.
(4) The lowest embodied CO_2 emissions of 319.89 $kgCO_2/m^3$ were exhibited by MS100, in which a total of 40% OPC substitution was done (30% FA and 10% MK). In addition to the reduced CO_2 emissions, MS100 achieved slightly better strength than MS00 of 79.31 MPa, which is 1.78% higher than MS100.
(5) The highest eco-strength efficiency of 0.268 $MPa/kgCO_2{\cdot}m^{-3}$ with respect to 28-day compressive strength was exhibited by MS101. This was achieved due to MS101 exhibiting the second highest 28-day compressive strength among the mixes.
(6) The least cost will be incurred by MS00, which is $102.5 per m^3 of concrete. The addition of MK and NS increased the cost. The lowest cost of producing 1 MPa was exhibited by MS01 with a merely 0.04-$/MPa/$m^3$ reduction compared to MS00.

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Declarations

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Conflict of interest The authors declare no competing interests.

References

Abd Elrahman M, Hillemeier B (2014) Combined effect of fine fly ash and packing density on the properties of high performance concrete: an experimental approach. Constr Build Mater Elsevier Ltd 58:225–233. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061814001792

Adamu M, Mohammed BS, Shahir Liew M (2018) Mechanical properties and performance of high volume fly ash roller compacted concrete containing crumb rubber and nano silica. Constr Build Mater [Internet] 171:521–538 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061818306354

Ahad MZ, Ashraf M, Kumar R, Ullah M (2019) Thermal, physico-chemical, and mechanical behaviour of mass concrete with hybrid blends of bentonite and fly ash. Materials (Basel) Multidisciplinary Digital Publishing Institute 12(1):60. Available from: https://doi.org/10.3390/ma12010060

Alnahhal MF, Alengaram UJ, Jumaat MZ, Abutaha F, Alqedra MA, Nayaka RR (2018) Assessment on engineering properties and CO_2 emissions of recycled aggregate concrete incorporating waste products as supplements to Portland cement. J Clean Prod [Internet] 203:822–835 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652618326532

ASTM C618 - 19 (2019) Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. ASTM International, West Conshohocken, PA

ASTM C597 - 16 (2016) Standard test method for pulse velocity through concrete. ASTM International, West Conshohocken, PA

ASTM C1202 - 19 (2019) Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. ASTM International, West Conshohocken, PA

Bagheri AR, Zanganeh H (2012) Comparison of rapid tests for evaluation of chloride resistance of concretes with supplementary cementitious materials. J Mater Civ Eng 24:1175–1182. Available from: https://doi.org/10.1061/(ASCE)MT.1943-5533.0000485

Baioumy H, Ibrahim AR (2012) Mineralogical variations among the kaolin deposits in Malaysia. Annu Int Conf Geol Earth Sci. Available from: https://www.researchgate.net/publication/265385508_Mineralogical_Variations_among_the_Kaolin_Deposits_in_Malaysia

Benhelal E, Zahedi G, Shamsaei E, Bahadori A (2013) Global strategies and potentials to curb CO_2 emissions in cement industry. J Clean Prod [Internet] 51:142–161 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652612006129

Berra M, Carassiti F, Mangialardi T, Paolini AE, Sebastiani M (2012) Effects of nanosilica addition on workability and compressive strength of Portland cement pastes. Constr Build Mater Elsevier Ltd 35:666–675. Available from:https://linkinghub.elsevier.com/retrieve/pii/S0950061812003364

Bharatkumar BH, Narayanan R, Raghuprasad BK, Ramachandramurthy DS (2001) Mix proportioning of high performance concrete. Cem Concr Compos Elsevier 23(1):71–80. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0958946500000718

Bheel N, Mahro SK, Adesina A (2021) Influence of coconut shell ash on workability, mechanical properties, and embodied carbon of concrete. Environ Sci Pollut Res 28(5):5682–5692 Available from: http://link.springer.com/10.1007/s11356-020-10882-1

BS EN 12390-6 (2009) Testing hardened concrete. Tensile splitting strength of test specimens. BSI Stand Ltd

BS EN 12390-3 (2019) Testing hardened concrete. Compressive strength of test specimens. BSI Stand Ltd

BS EN 12390-5 (2019) Testing hardened concrete. Flexural strength of test specimens. BSI Stand Ltd

Damineli BL, Kemeid FM, Aguiar PS, John VM (2010) Measuring the eco-efficiency of cement use. Cem Concr Compos [Internet] 32(8): 555–562 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0958946510000958

Dinakar P, Manu SN (2014) Concrete mix design for high strength self-compacting concrete using metakaolin. Mater Des Elsevier 60:661–668 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0261306914002465

El-Din HKS, Eisa AS, Aziz BHA, Ibrahim A (2017) Mechanical performance of high strength concrete made from high volume of Metakaolin and hybrid fibers. Constr Build Mater Elsevier 140: 203–209 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061817303161

Flores-Vivian I, Pradoto R, Moini M, Sobolev K (2013) The use of nanoparticles to improve the performance of concrete. Nano Conf. Available from: https://www.researchgate.net/publication/258510750_THE_USE_OF_NANOPARTICLES_TO_IMPROVE_THE_PERFORMANCE_OF_CONCRETE

Flower DJM, Sanjayan JG (2007) Green house gas emissions due to concrete manufacture. Int J Life Cycle Assess [Internet] 12(5): 282–288 Available from: http://link.springer.com/10.1065/lca2007.05.327

García-Segura T, Yepes V, Alcalá J (2014) Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. Int J Life Cycle Assess [Internet] 19(1):3–12 Available from: http://link.springer.com/10.1007/s11367-013-0614-0

Ghafari E, Costa H, Júlio E, Portugal A, Durães L (2014) The effect of nanosilica addition on flowability, strength and transport properties of ultra high performance concrete. Mater Des [Internet] 59:1–9 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0261306914001691

Güneyisi E, Gesoğlu M, Algin Z, Mermerdaş K (2014) Optimization of concrete mixture with hybrid blends of metakaolin and fly ash using response surface method. Compos Part B Eng 60:707–715 Available from: https://linkinghub.elsevier.com/retrieve/pii/S1359836814000274

Islam J (2011) Use of nano-silica to increase early strength and reduce setting time of concretes with high volumes of slag or fly ash. (Masters thesis). Available from: https://core.ac.uk/download/pdf/48639732.pdf

Jalal M, Pouladkhan A, Harandi OF, Jafari D (2015) Comparative study on effects of class F fly ash, nano silica and silica fume on properties of high performance self compacting concrete. Constr Build Mater Elsevier Ltd 94:90–104. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061815300234

Jhatial AA, Goh WI, Mastoi AK, Rahman AF, Kamaruddin S (2021) Thermo-mechanical properties and sustainability analysis of newly developed eco-friendly structural foamed concrete by reusing palm oil fuel ash and eggshell powder as supplementary cementitious materials. Environ Sci Pollut Res. Available from: http://link.springer.com/10.1007/s11356-021-13435-2

Khatib JM, Clay RM (2004) Absorption characteristics of metakaolin concrete. Cem Concr Res [Internet] 34(1):19–29 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0008884603001881

Kumar R, Mohd Yaseen AYB, Shafiq N, Jalal A (2017) Influence of metakaolin, fly ash and nano silica on mechanical and durability properties of concrete. Key Eng Mater [Internet] 744:8–14 Available from: https://www.scientific.net/KEM.744.8

Kwan AKH, Wong HHC (2008) Packing density of cementitious materials: part 2—packing and flow of OPC+ PFA+ CSF. Mater Struct Springer 41(4):773–784. Available from: https://link.springer.com/article/10.1617/s11527-007-9281-6

Lamond JF, Pielert JH (2006) Significance of tests and properties of concrete and concrete-making materials. (West Conshohocken, PA: ASTM International, 2006). Available from: https://doi.org/10.1520/STP169D-EB

Lenka S, Panda KC (2017) Effect of metakaolin on the properties of conventional and self compacting concrete. Adv Concr Constr 5(1):31–48. Available from: https://doi.org/10.12989/acc.2017.5.1.31

Li LG, Zheng JY, Ng PL, Zhu J, Kwan AKH (2019) Cementing efficiencies and synergistic roles of silica fume and nano-silica in sulphate and chloride resistance of concrete. Constr Build Mater Elsevier 223:965–975. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061819319191

Li LG, Zheng JY, Zhu J, Kwan AKH (2018) Combined usage of micro-silica and nano-silica in concrete: SP demand, cementing efficiencies and synergistic effect. Constr Build Mater Elsevier 168:622–632. Available from: https://linkinghub.elsevier.com/retrieve/pii/S095006181830432X

Liew YM, Kamarudin H, Mustafa Al Bakri AM, Luqman M, Khairul Nizar I, Ruzaidi CM et al (2012) Processing and characterization of calcined kaolin cement powder. Constr Build Mater [Internet] 30: 794–802 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061811007690

Long G, Gao Y, Xie Y (2015) Designing more sustainable and greener self-compacting concrete. Constr Build Mater [Internet] 84:301–306 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061815002263

Maddalena R, Roberts JJ, Hamilton A (2018) Can Portland cement be replaced by low-carbon alternative materials? A study on the thermal properties and carbon emissions of innovative cements. J Clean Prod [Internet] 186:933–942 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652618304505

Mardani-Aghabaglou A, Inan Sezer G, Ramyar K (2014) Comparison of fly ash, silica fume and metakaolin from mechanical properties and durability performance of mortar mixtures view point. Constr Build Mater 70:17–25 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061814008514

Meddah MS, Ismail MA, El-Gamal S, Fitriani H (2018) Performances evaluation of binary concrete designed with silica fume and metakaolin. Constr Build Mater [Internet] 166:400–412 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061818301624

Nath P, Sarker PK (2013) Effect of mixture proportions on the drying shrinkage and permeation properties of high strength concrete containing class F fly ash. KSCE J Civ Eng Springer 17(6):1437–1445 Available from: https://doi.org/10.1007/s12205-013-0487-6

Nazari A, Riahi S (2011) The effects of SiO_2 nanoparticles on physical and mechanical properties of high strength compacting concrete. Compos Part B Eng Elsevier Ltd 42(3):570–578 Available from: https://linkinghub.elsevier.com/retrieve/pii/S1359836810001666

Parande AK, Babu BR, Karthik MA, Kumaar KKD, Palaniswamy N (2008) Study on strength and corrosion performance for steel embedded in metakaolin blended concrete/mortar. Constr Build Mater Elsevier 22(3):127–134 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061806002844

Ramezanianpour AA, Bahrami JH (2012) Influence of metakaolin as supplementary cementing material on strength and durability of concretes. Constr Build Mater [Internet] 30:470–479 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061811007288

Rao VP, Maruthi SV (2016) Effect of nano-silica on concrete containing metakaolin. Int J Civ Eng Technol [Internet] 7(1):104–112 Available from: http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=1

Rashad AM (2015) An exploratory study on high-volume fly ash concrete incorporating silica fume subjected to thermal loads. J Clean

Prod [Internet] 87:735–744 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652614009482
Sabir BB, Wild S, Bai J (2001) Metakaolin and calcined clays as pozzolans for concrete: a review. Cem Concr Compos Elsevier 23(6):441–454 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0958946500000925
Said AM, Zeidan MS, Bassuoni MT, Tian Y (2012) Properties of concrete incorporating nano-silica. Constr Build Mater Elsevier Ltd 36:838–844 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061812004369
Saikia N, Kato S, Kojima T (2006) Thermogravimetric investigation on the chloride binding behaviour of MK–lime paste. Thermochim Acta [Internet] 444(1):16–25 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0040603106000888
Salimi J, Ramezanianpour AM, Moradi MJ (2020) Studying the effect of low reactivity metakaolin on free and restrained shrinkage of high performance concrete. J Build Eng Elsevier 28:101053 Available from: https://linkinghub.elsevier.com/retrieve/pii/S2352710219316304
Shafiq N, Kumar R, Zahid M, Tufail RF (2019) Effects of modified metakaolin using nano-silica on the mechanical properties and durability of concrete. Materials (Basel) [Internet] (14):12, 2291 Available from: https://www.mdpi.com/1996-1944/12/14/2291
Shafiq N, Nuruddin MF, Khan SU, Ayub T. Calcined kaolin as cement replacing material and its use in high strength concrete. Constr Build Mater [Internet]. 2015;81:313–23. Available from: https://linkinghub.elsevier.com/retrieve/pii/S095006181500197X
Sikora P, Rucinska T, Stephan D, Chung S-Y, Abd Elrahman M (2020) Evaluating the effects of nanosilica on the material properties of lightweight and ultra-lightweight concrete using image-based approaches. Constr Build Mater Elsevier 264:120241
Song HW, Lee CH, Ann KY (2008) Factors influencing chloride transport in concrete structures exposed to marine environments. Cem Concr Compos 30(2):113–121 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0958946507001527
Stefanidou M, Papayianni I (2012) Influence of nano-SiO_2 on the Portland cement pastes. Compos Part B Eng [Internet] 43(6):2706–2710 Available from: https://linkinghub.elsevier.com/retrieve/pii/S1359836812000066
Suhendro B (2014) Toward green concrete for better sustainable environment. Procedia Eng [Internet] 95:305–320 Available from: https://linkinghub.elsevier.com/retrieve/pii/S1877705814032494
Sujjavanich S, Suwanvitaya P, Chaysuwan D, Heness G (2017) Synergistic effect of metakaolin and fly ash on properties of concrete. Constr Build Mater Elsevier 155:830–837 Available from: https://linkinghub.elsevier.com/retrieve/pii/S095006181731663X
Turner LK, Collins FG (2013) Carbon dioxide equivalent (CO_2-e) emissions: a comparison between geopolymer and OPC cement concrete. Constr Build Mater [Internet] 43:125–130 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061813000871
U.S. Geological Survey (2019) Mineral commodity summaries 2019 [Internet]. Available from: https://www.usgs.gov/centers/nmic/mineral-commodity-summaries
Valipour M, Pargar F, Shekarchi M, Khani S (2013) Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: a laboratory study. Constr Build Mater Elsevier 41:879–888 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0950061812008902
Wang J, Wu X, Wang J, Liu C, Lai Y, Hong Z et al (2012) Hydrothermal synthesis and characterization of alkali-activated slag–fly ash–metakaolin cementitious materials. Microporous Mesoporous Mater [Internet] 155:186–191 Available from: https://linkinghub.elsevier.com/retrieve/pii/S1387181112000261
Wild S, Khatib JM, Jones A (1996) Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete. Cem Concr Res Elsevier 26(10):1537–1544 Available from: https://linkinghub.elsevier.com/retrieve/pii/0008884696001482
Xi F, Davis SJ, Ciais P, Crawford-Brown D, Guan D, Pade C et al (2016) Substantial global carbon uptake by cement carbonation. Nat Geosci [Internet] 9(12):880–883 Available from: http://www.nature.com/articles/ngeo2840
Yang K-H, Song J-K, Song K-I (2013) Assessment of CO_2 reduction of alkali-activated concrete. J Clean Prod [Internet] 39:265–272 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0959652612004076
Zareei SA, Ameri F, Bahrami N, Shoaei P, Moosaei HR, Salemi N (2019) Performance of sustainable high strength concrete with basic oxygen steel-making (BOS) slag and nano-silica. J Build Eng Elsevier 25:100791 Available from: https://linkinghub.elsevier.com/retrieve/pii/S2352710218311951
Ženíšek M, Vlach T, Laiblová L (2016) Dosage of metakaolin in high performance concrete. Key Eng Mater [Internet] 722:311–315 Available from:https://www.scientific.net/KEM.722.311
Zhang J, Liu G, Chen B, Song D, Qi J, Liu X (2014) Analysis of CO_2 emission for the cement manufacturing with alternative raw materials: a LCA-based framework. Energy Procedia 61:2541–2545 Available from: https://linkinghub.elsevier.com/retrieve/pii/S1876610214030707
Zhang YJ, Li S, Wang YC, Xu DL (2012) Microstructural and strength evolutions of geopolymer composite reinforced by resin exposed to elevated temperature. J Non Cryst Solids [Internet] 358(3):620–624 Available from: https://linkinghub.elsevier.com/retrieve/pii/S0022309311006806
Zhuang C, Chen Y (2019) The effect of nano-SiO_2 on concrete properties: a review. Nanotechnol Rev [Internet] 8(1):562–572 Available from: https://www.degruyter.com/document/doi/10.1515/ntrev-2019-0050/html

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