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HIGH VOLUME BRICK POWDER CONCRETE SYNERGISTIC WITH METAKAOLIN: PHYSICOMECHANICAL PROPERTIES AND DRYING SHRINKAGE

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ABSTRACT

Currently, sustainability of the construction and building industry taken a priority. This study investigates the feasibility of using a high volume (up to 50%) of blended waste brick powder (BP) and metakaolin (MK) as ordinary Portland cement (OPC) replacements. The binder of the control mixture was a blend of 50% OPC and 50% BP, while the other two mixes were prepared by substituting 10% and 20% of BP with MK. The characteristics of fresh concrete were assessed depending on measuring the mixture temperature, the fresh density, and the workability. The bulk density, and the mechanical properties were investigated and tested at 7 and 28 days. In the line of durability parameters, the void content and drying shrinkage up to 90 days of all mixtures were evaluated. The findings have demonstrated that the control mixture achieved high workability (slump =180 mm), structural compressive strength (34 MPa) at 28 days, low void content (<3%), and acceptable shrinkage strain. The workability of the mixes containing 10%MK:40%BP and 20%MK:30%BP has slightly decreased, while the mechanical properties were increased and the drying shrinkage were declined. However, the inclusion of This study highlighted an ecological technique toward waste management of construction materials and confirmed the possibility of including a high volume of BP as a cementitious material to synthesize more sustainable concrete.

KEYWORDS

Waste brick powder, Metakaolin, Mechanical properties, Drying shrinkage, Sustainability.

1. INTRODUCTION

One of the major crisis that facing the world is climate change as a consequence of global warming. The United Nation (UN) report "Emission Gap Report 2022: The closing window" states that a 45% reduction in greenhouse gas emissions must be achieved to limit global warming to 1.5 °C by 2030 (UN: Emission gas report; 2022). The building industry plays a significant role in global emissions, both directly and indirectly. Concrete is an extremely used construction material in the building industry, with an annual consumption of 10 billion tons, and the estimation is that it will rise to 18 billion tons in the coming years (Mousavinejad et al., 2023). Manufacturing of one kilogram ordinary Portland cement (OPC), will emits about 0.66 to 0.82 of carbon dioxide (CO_2) (Shamsa et al., 2021). This production will contributes for 8% of global emissions, and has substantial environmental consequences due to high energy consumption and depletion of raw materials. The rapid population growth and development of urbanized cities have led to a significant increase in global cement output over time. In 2008, the production reached 2.6 billion tons, and by 2020, it had risen to 3.5 billion tons (Spelmana and Lee, 2022), and the demand for cement will increase by more than 48% by 2050 (Skinner and Lalit, 2023) according to estimates. On the other hand, the construction sector negatively impacts the environment by generating a significant volume of construction and demolition waste. This waste mostly comprises clay bricks generated during manufacturing, construction, expansion, and demolition activities. These wastes are usually dumped in landfills or deposited in open areas, leading to serious environmental pollution (Helmy et al., 2023). Therefore, there is an urgent desire to address the disposal of this waste, considering its economic and environmental sustainability. The reuse and recycling of waste bricks as ingredients in concrete production can be an ecological solution to cut down a substantial amount of CO_2 emission and the disposal of construction waste. According to the broad recommendations of the United Nations Report 2022 into encouragement of studies and projects aiming at zero carbon emissions, and compliance with sustainability concerns in concrete production, many researchers have performed numerous investigations on the properties of concrete mixes made from recycled waste brick as a fine and coarse aggregate (Wong et al., 2018; Khalil and Al-Daebal, 2018; Islam et al., 2024; Zhao et al., 2024; and Tang et al., 2020). However, there are extensive studies that have been reported on the possibility of including waste brick powder as supplementary cementitious materials in concrete and mortar. (Salman and Yousif, 2018), conducted a study where they replaced a portion of the cement content with yellow clay brick powder at various percentages: 5%, 10%, 15%, 20%, 25%, 50% and 100%. Additionally, they adjusted the concrete mixes by adding 10% micro silica fume. The findings indicate that the workability decreases as the amount of brick powder increases, whereas the mechanical properties enhance with 5% brick powder as the optimum dosage. (Mao et al., 2019) developed an environmentally friendly reactive powder concrete by substituting 10%, 20% and 30% of the cement with recycled powder. The ratio of recycled powder produced from construction material waste containing bricks and concrete is 7:3. The researchers discovered that when the percentage of recycled powder in the reactive powder combinations increased, the mixtures' flow, compressive strength, and flexural strength all decreased. On the other hand, (Bayraktar et al., 2019) investigated the high temperature affects the mechanical properties of cement mortar with different levels (5%, 10%, 15%, and 20%) of waste brick dust. The primary conclusions of the research conducted by (Ma et al., 2020) indicate that when the waste brick powder concentration increases from 7.5% to 30%, there is a decrease in both compressive and flexural strength. Using an optimal amount of (WBP) as a substitute for cement will decrease the amount of water absorbed by cement mortar. Similarly, other studies have replaced cement with waste brick powder as pozzolanic materials in the manufacturing of concrete, mortar, and paste, utilizing varying proportions: The percentages listed are as follows: 2.5%, 5%, 7.5%, and 10% (Sinkhonde et al., 2021); 10%, 20%, and 30% (Xue et al., 2021); 5%, 10%, and 20% (Shah et al., 2021; Rumin´ski et al., 2022); 5% and 10% (Arif et al., 2021) and 5% for cement paste (Sinkhonde and Mashava, 2022). Moreover, (Mansoor et al., 2022) assessed the impact of substituting the ordinary Portland cement (OPC) in mortar mixes with brick powder at varying ratios ranging from 10% to 50% on the parameters related to the fresh state, mechanical strength, and absorption-sorptivity. The optimum amount of brick powder for achieving maximum compressive strength and water transmission was found to be 15%. Another study by (Wang et al., 2022) investigated the strength, durability properties, and environmental impact of eco-friendly mortars when the OPC was replaced with 10%, 20%, and 30% grinding brick powder along with metakaolin (MK) at ratios of 0%, 5%, 10%, and 15% for each mix. The conclusion indicated that the optimum binder proportion with respect to the objective criteria was 70% OPC, 20% BP, and 10% MK. Incorporating waste brick powder into the production of special types of concrete has also been the focus of other researchers. This includes self-compacting concrete with dosages of 5% and 12.5% (Wolde et al., 2023), roller compacted concrete with levels of 5% and 10%, (Tarrad and Abbas, 2023) or 10%, 20%, 30% and 40% (Yaseen et al., 2024). Although the use of waste brick as a cementitious material and its effects on the performance of cement-based composites have been widely investigated, there is limited literature considering the substitution of a high volume of OPC with waste brick powder in concrete production. Hence, to overcome this research gap, a high volume of waste brick powder (50%) has been substituted with OPC to create a sustainable concrete mixture. Furthermore, the effects of blending 10% and 20% MK with 40% and 30% BP respectively on the properties of this green concrete is examined. The goal of this study is to evaluate the workability, mechanical and some physical properties of the high volume brick powder (HVBP) concrete. Additionally, it aims to determine the optimum proportion of OPC (BP/MK) ternary binder to enhance the performance of HVBP concrete in terms of workability, structural strength, and durability.

2. EXPERIMENTAL WORK

2.1. Materials

2.1.1. Cement

In this study, ordinary Portland cement Type (I) confirming to Iraqi specification (IQ.S No. 5-1985) was used for all mixtures. The chemical composition and physical properties are presented in Table 1.

2.1.2. Metakaolin

Locally kaolinite clay has burned up to 700 °C for two hours to produce metakaolin to be used in this research. Table 1 lists the chemical and physical properties.

2.1.3. Brick powder

The waste of clay brick has been collected, crushed into small particles, and then ground by cyclone grinder machine at a local factory in Baghdad City to produce brick powder. The final BP is shown in Fig. 1, and the details of the chemical and physical properties listed in Table 1. The waste brick powder complies with (ASTM C618, 2017) requirements as natural pozzolan.

Fig. 1. Waste clay brick powder

Table 1. Chemical analysis and physical properties for OPC, MK, and BP

Chemical oxides (%)*	OPC	BP	MK
CaO	61.9	20.2	1.37
SiO_2	21.7	56.82	54.2
Al_2O_3	4.67	11.41	39
Fe_2O_3	3.33	2.38	0.92
MgO	3.91	3.02	0.15
SO_3	2.50	0.83	0.45
Na_2O	/	0.84	0.22
K_2O	/	0.81	0.27
L.O.I	2.24	1.19	0.71
Physical properties*			
Specific gravity	3.14	2.84	2.64
Specific surface area, (m^2/kg)	390	462	14300
Particles size D50, µm	/	138	17.63
Compressive strength at 7 days, (MPa)	27.1	/	/
Pozzolanic activity index at 7 days, (%)	/	89.2	113.3

* The tests were carried out in the Iraq geological survey, central laboratories department.

2.1.4. Natural aggregate

The coarse aggregate was graded crushed gravel of 14 mm maximum sizes and 2.68 specific gravity, confirming to (IQ.S No.45-1985). Locally available natural sand with 4.75 mm maximum particles size and 2.86 fineness modulus was used as fine aggregate, confirming to zone II according to IQ.S No.45-1985.

2.1.5. Superplasticizer

A high range water-reducing admixture based on sulphonated naphthalene polymers, commercially known as superplasticizer (SP 2000) has been used to improve the workability of the mixtures in this study. The main properties of the superplasticizer according to the manufacturer report are illustrated in Table 2.

Table 2. Technical properties of superplasticizer SP 2000 – Conplast

Properties	Details
Color	Brown liquid
Freezing point	-2˚C approximately
Specific gravity	1.215 at 25°C
Air entrainment, %	Typically less than 2
Alkali content	56.6 g Na2O equivalent/litter of admixture
Chloride content	Nil
Fire	Non- flammable

2.1.6. Water

Tap water free from contaminants has been used for concrete preparation and specimen curing.

2.2. Mix proportion and preparation of samples

The experimental approach was based on a control mixture that contain waste brick powder as 50% of the cementitious binder weight. Several trial mixes were conducted to design the reference mix for a target strength up to 30 MPa at 28 day. In addition to the reference mix, two mixes are prepared by replacing 10% and 20% BP with metakaolin (MK). All the mixes have the same (water: binder) ratio, and superplasticizer dosage at 0.3 and 2%, respectively. The quantity of materials and mix proportion, along with the name of each mixture, are exhibited in Table 3.

Table 3. Mixing proportions and identification of concrete mixtures

Materials, (kg/m^3)	Mixtures Code		
	M1(50BP:0MK)	M2(40BP:10MK)	M3(30BP:20MK)
OPC	225	225	225
BP	225	180	135
MK	0	45	90
Gravel	1075	1075	1075
Sand	718	718	718
Water	135	135	135
SP	9	9	9

All concrete mixtures were prepared using the same procedure. Firstly, the dry materials including cement; brick powder; coarse and fine aggregates were mixed thoroughly inside an electrical mixer. Then, the water and superplasticizer were added gradually without stopping the mixer until achieving a homogenous mixture. The fresh concrete was cast in the required moulds and vibrated on a vibrating table to remove entrapped air. The casted moulds were covered with plastic sheets to prevent losing of moisture and kept to setting for 24 hr. Finally, the samples were demoulded and cured by immersion in water until the testing time.

2.3. Testing methods

For characterizing the properties of high volume brick powder concrete, the following tests were conducted on the fresh and hardened concrete specimens, as presented in Table 4. The temperature of the fresh concrete inside the mixer pan was measured immediately after stopping the mixing process. At the same time, slump tests and flow table tests were conducted to determine the workability of fresh concrete.

The temperature of coarse aggregate, fine aggregate and water were kept constant and used at the same conditions to mitigate the variation of fresh concrete temperature.

The cubes of 150 mm were used to evaluate the fresh density and then to assess the compressive strength at ages 7 and 28 days. On the other hand, the flexural strength and splitting tensile strength of the concrete mixtures were evaluated at ages 7 and 28 days using prism specimens of 100×100×500 mm and cylinders of 100×200 mm, respectively. After the splitting strength test was done, the fractured cylinders (half cylinder) were used to determine the bulk density and voids content of hardened concrete mixtures. All specimens were chosen to ensure they were free of any visible cracks, fissures, or fragmented edges. For all tests, the average of three tested specimens was taken as the result for each age. All mixes were tested after 28 days of curing to measure the permeable pore space in accordance with (ASTM C642, 2013). This test give an indication about the voids content within concrete matrix.

Table 4. The experimental tests and specifications

Test	Standard used
Temperature of fresh concrete	(ASTM C1064,2017)
Slump	(ASTM C143, 2012)
Flow table	(BS EN 12350-5, 2009)
Fresh density	(ASTM C138, 2017)
Bulk density	(ASTM C642, 2013)
Voids	(ASTM C642, 2013)
Compressive strength	(B.S. 1881 part 116, 1983)
Flexural strength	(ASTM C78, 2009)
Splitting tensile	(ASTM C496, 2017)

Prisms measuring 100 x 100 x 300 mm were used to measure the drying shrinkage. After the specimens were demoulded, all samples were stored inside a room with an average temperature of 30°C and a relative humidity of 65%. The drying shrinkage test was conducted in line with (ASTM C157, 2003). The testing approach involved using an extensometer device to consistently gauge changes in length between two stainless steel disks affixed to the sidewalls of the specimens at intervals of 1, 7, 14, 28, 56, and 90 days. Fig.2 shows the prismatic specimens and the instrument for the drying shrinkage test.

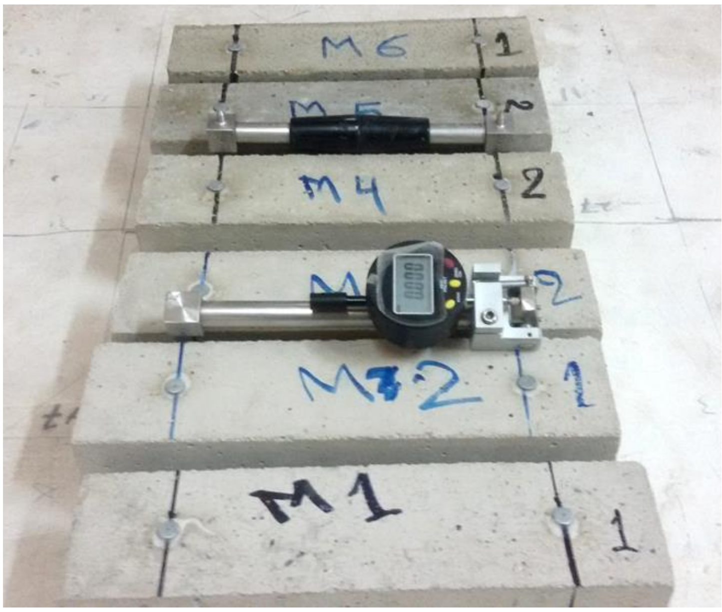

Fig. 2. Specimens and approach of drying shrinkage test

3. RESULTS AND DISCUSSION

3.1. Temperature of fresh concrete

The temperature of fresh concrete is an important characteristic that directly influences the strength and longevity of the concrete. Most of this heat is gained through the cement hydration reaction, in addition to the temperature of the other concrete ingredients and the weather.

Fig. 3 shows the variation in temperature for all mixtures. It can be observed that the highest recorded temperature was 36.5 °C for mix M1 (50BP:0MK) content. With the increase of metakaolin to brick powder ratio content up to 10:40% and 20:30%, the fresh concrete temperature decreased to be 35.8 °C and 34.8 °C, respectively. This reduction can be attributed to the change in the hydrate phase, as the chemical composition of the main binder changes.

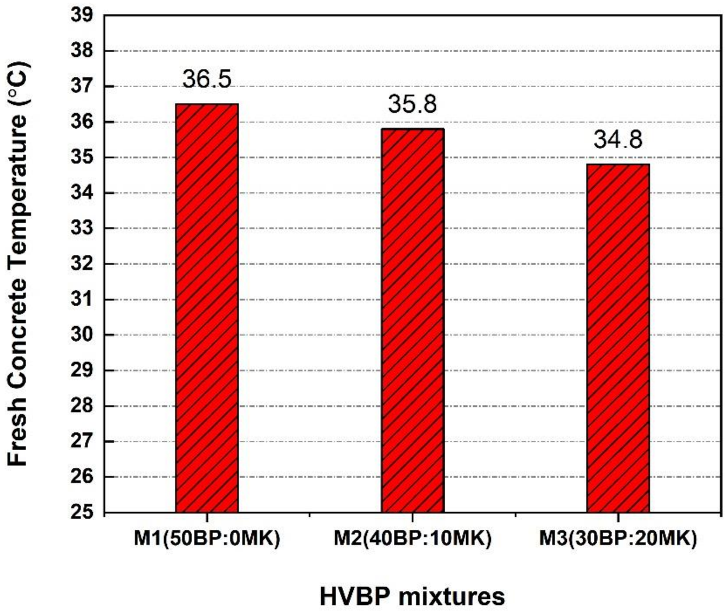

Fig. 3. Temperature of fresh concrete mixtures

3.2. Workability

Fig.4 shows the slump values for all HVBP concrete mixtures. The control mixture (M1) exhibits a slump measurement of 180 millimeters. By replacing 10% and 20% of BP with MK, the slump value will experience a slight reduction of 1.67% and 8.33% respectively.

In order to obtain a better understanding of the workability of high-volume blended brick powder concrete, the consistency of the mixtures was assessed by means of a flow table test. Fig. 5 illustrates that the flow result of the control mix was 580 mm, demonstrating a satisfactory dispersion. The spread diameter of fresh concrete has decreased by 2.58% and 8.10% for mixtures containing 10% and 20% MK content, respectively. This finding is related to the high fineness and irregular shape of MK particles which have adverse effects on concrete consistency and workability (Frieh et al., 2014) and (Siddique & Khan , 2011).

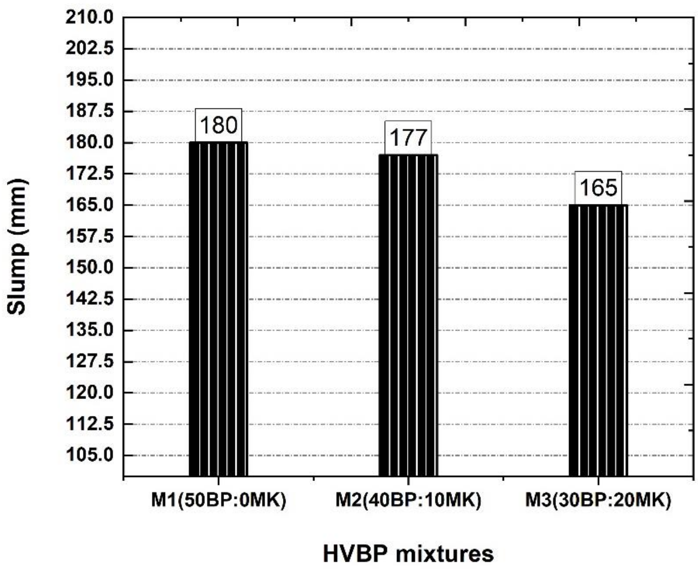

Fig. 4. Slump values of concrete mixtures

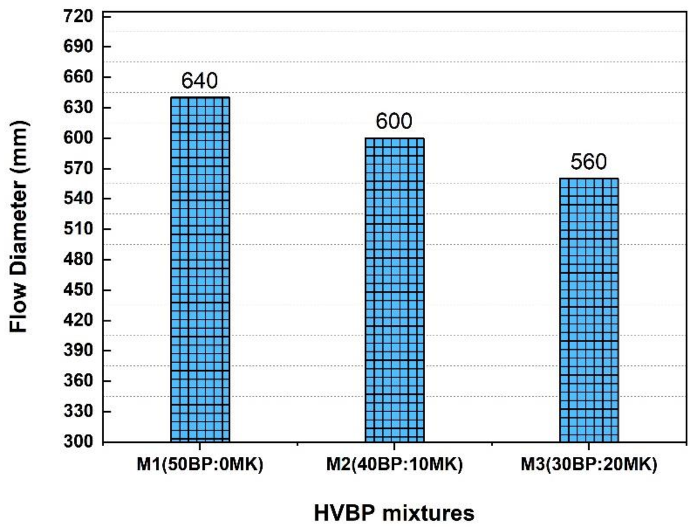

Fig. 5. Flow table results of the mixtures

3.3. Fresh density

Fig.6 illustrates the findings about the density of fresh specimens. The fresh density of the control mix, with a 50% BP content, was measured to be 2437 kg/m3. With a 10% and 20% increase in MK content, the fresh density experienced a slight increase of 1.19% and 3.0%, respectively. The reason can be related to the filling ability of MK and providing a more cohesive mixture with less entrapped air. As a result, the amount of fine ingredients in the concrete will increase, leading to a denser composite. This observation has been also noticed visually while mixing and preparing the concrete. Due to the presence of MK in the fresh mixtures, they exhibit higher bulk, weight, and cohesiveness.

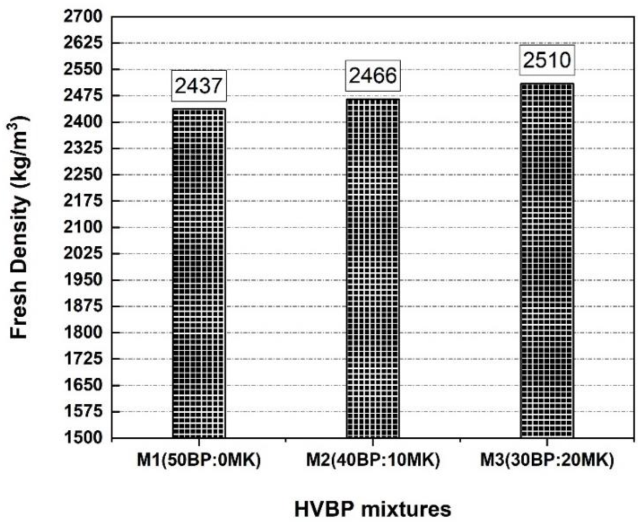

Fig. 6. Fresh density of the concrete mixtures

3.4. Bulk density

The dry density of all mixes after curing for 7 and 28 days is depicted in Fig. 7. The dry densities slowly but surely increased over time as a result of the ongoing development of cement gel and the decrease in voids within the concrete matrix. The measured densities of the control mixture after 7 and 28 days were 2349 and 2361 kg/m3, respectively. The results indicate that the addition of 10% MK has resulted in a minor increase in the bulk density of the reference mix, with increases of 0.38% and 0.34% seen at 7 and 28 days, respectively. By incorporating 20% MK, the dry density decreased by approximately 0.64% after 7 days and 0.25% after 28 days. The variations in the dry density of the mixtures can be attributed to the optimal compatibility reaction between the ternary binder consisting of ordinary Portland Cement (OPC), Metakaolin (MK), and brick powder (BP). Therefore, the combination of 10% MK and 40% BP in the mixture will result in a higher quantity of gel and a smaller number of voids in the microstructure of concrete (Ramezanianpour, 2014) and (Siddique & Khan , 2011).

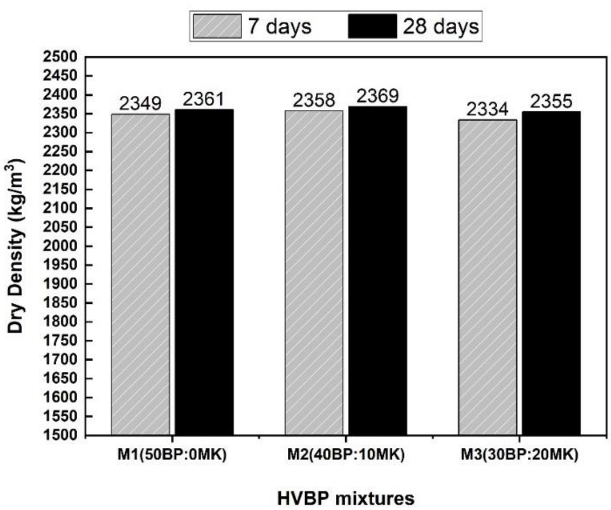

Fig. 7. Dry density of all HVBP concrete mixtures at 7 and 28 days

3.5. Voids content

Fig. 8 shows the total void volume that exists within the HVBP concrete mixtures after 28 curing days. The control mix exhibits a permeable pore space of 2.52%. By substituting 10% and 20% of BP weight with MK, the void content declined by 6.74% and 6.35% respectively. The decrease in void content can be ascribed to the synergistic impact of MK, a highly pozzolanic reaction that generates additional gel and enhances the filling capacity due to the fine particles of MK. These particles improve the pore system and densely pack within the interfacial transition zone. The addition of 10% MK to the 40% BP will alter the microstructure and the morphology of the cement paste, leading to the formation of a more compact concrete with reduced void content.

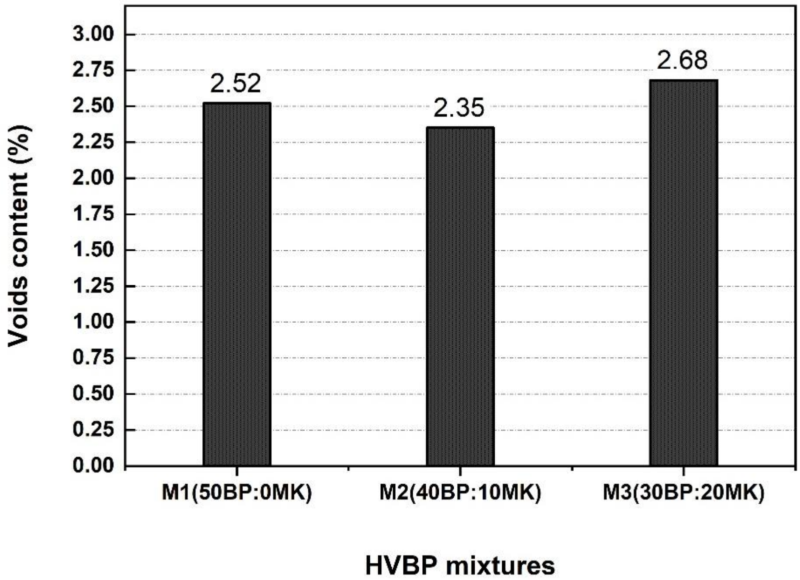

Fig. 8. Voids content of the mixtures at 28 days

3.6. Compressive strength

The cubic compressive strength of each mixture is shown in Fig. 9, after being cured for 7 and 28 days. The results showed that the reference mixture (50% BP: 50% OPC) gained a strength of 25.6 MPa at 7 days, which then increased to 34.9 MPa at 28 days. The substitution of BP by 10% and 20% MK has improved the compressive strength of concrete. It is seen that the inclusion of 10% MK has increased the compressive strength by 61.5% and 28.8% after 7 and 28 days, respectively. Meanwhile, the strength of the mixture with 20% MK increased by 37.6% at 7 days and 10.77% at 28 days. Generally, the strength activity index and chemical composition, as presented in Table 1, demonstrate the pozzolanic index of waste brick powder. Therefore, the synergic of brick powder at high volume with OPC can be a binary binder to manufacture concrete with sufficient strength. On the other hand, the pozzolanic activity reaction may be responsible for the increase in compressive strength that occurs as a consequence of using MK. More gel will be produced as a result of the reaction between the high concentration of silica and alumina oxides and the abundant amount of CaOH. Furthermore, the exceptional fineness of MK particles will improve the microstructure of the concrete matrix. The MK functions as a filler material in the cement paste composite, serving to both refine the voids and fill the gaps in the interfacial transition zone. Obviously, the strength development up to 28 days of mixtures that containing 50% BP is higher than mixes of 10% and 20% MK. This results indicated the slow gain strength of cementitious binder paste with high volume of BP. On contrast of that, the inclusion of MK accelerates the strength gain at early age due to the high pozzolanic activity of MK. (Newman & Choo, 2003), (Siddique & Khan , 2011), (Ramezanianpour, 2014), (Frieh et al., 2014) and (El-Din et al., 2017).

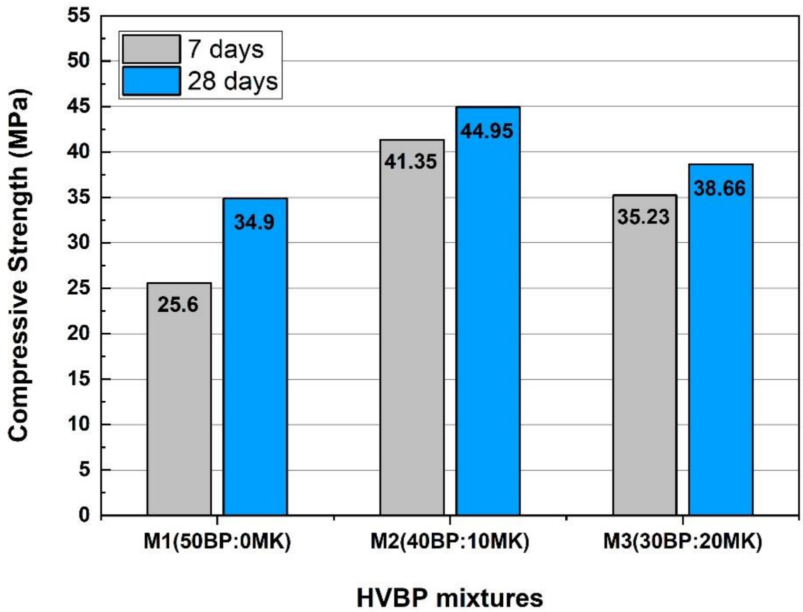

Fig. 9. Compressive strength of the mixtures at 7 and 28 days

3.7. Flexural strength

Fig. 10 depicts the flexural strength results of the mixes at ages of 7 and 28 days. The flexural strength of the control mix ranged from 3.9 MPa to 4.7 MPa after 7 and 28 days, respectively. The findings demonstrate that the addition of MK instead of brick powder (BP) leads to an increase in flexural strength at both ages. Nevertheless, the highest increment of modulus of rupture was 29.78%, specifically achieved with a 10% addition of MK after 28 days. In contrast, the increase in modulus of rupture for the mixture containing 20% MK after 28 days was 15.95%. The increase of flexural strength can be attributed to the pozzolanic reaction and the filler effect of MK within the cement paste.

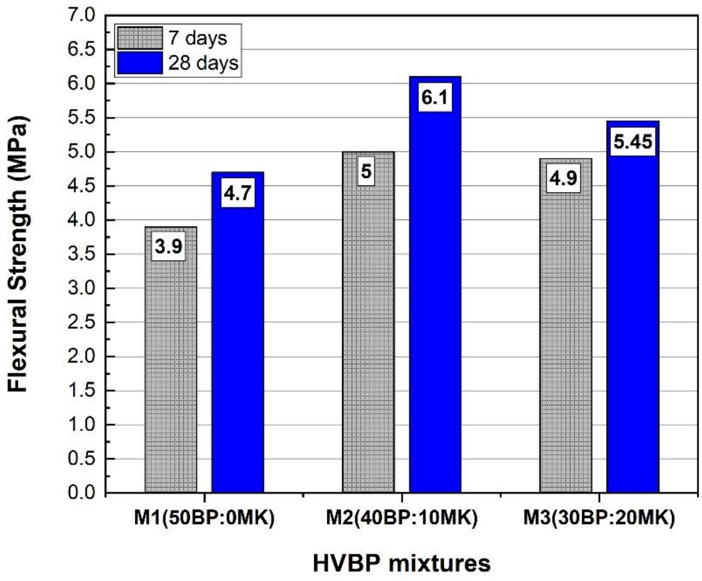

Fig. 10. Flexural strength of the mixtures at 7 and 28 days

3.8. Splitting tensile strength

The values of splitting tensile strength of the different mixes at ages 7 and 28 days are shown in Fig. 11. It can be seen that the splitting strength of the control mix reaches 2.4 MPa and 2.8 MPa after 7 and 28 days of curing, respectively. Similar to the findings of the compressive and flexural strength results, the substitution of BP with 10% and 20% MK will enhance the splitting strength. At the age of 28 days, the splitting strength of cylinders containing 10% MK increased up to 21.42%, versus 12.50% for specimens containing 20% MK. Because of the concrete composite under direct tensile load is affected by the cement paste strength, bonds with aggregate and the microstructure. Thus, the increase in tensile strength is mostly due to the MK exceptional pozzolanic reaction, which generates extra C-S-H gel, fills the voids, and refines the pores, resulting in a more compact concrete with enhanced microstructure (Newman & Choo, 2003), (Siddique & Khan , 2011), (Ramezanianpour, 2014), and (Frieh et al., 2014).

3.9. Drying Shrinkage

The development rate of drying shrinkage with time is presented in Fig. 12. It can be seen that the drying shrinkage of all mixes increased rapidly at an early age, up to 28 days. Then the increasing rate will slightly decline until the end of the test time. As shown in Fig.11, the reference mix with 50% BP content has expected higher drying shrinkage at all ages. The drying shrinkage of mixes that contain 10% and 20% MK was lower than the reference mix. For mix 40BP:10MK, the reduction of dry shrinkage reached 32.50%, 33.80%, 7.30%, and 4.68%, while mix 30BP:20MK showed a reduction up to 42.50%, 43.10%, 17.14%, and 16.25% after 1, 7, 28, and 90 days, respectively. The drying shrinkage is related to the loss of moisture content from the concrete matrix and especially from cement pastes. Thus, the inclusion of MK (which has high fineness) will consume the mixing water and consequently reduce the free water within the cement gel. Moreover, the effect of pozzolanic activity and refinement on the pores has increased the strength of concrete and, as a result, increased resistance against strains of length change (Newman & Choo, 2003) and (Ramezanianpour, 2014).

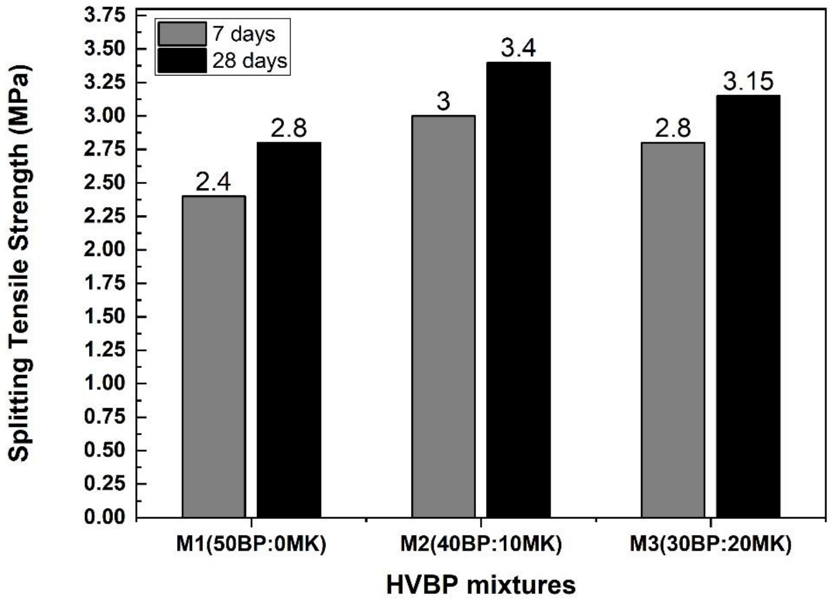

Fig. 11. Splitting tensile strength of the mixtures at 7 and 28 days

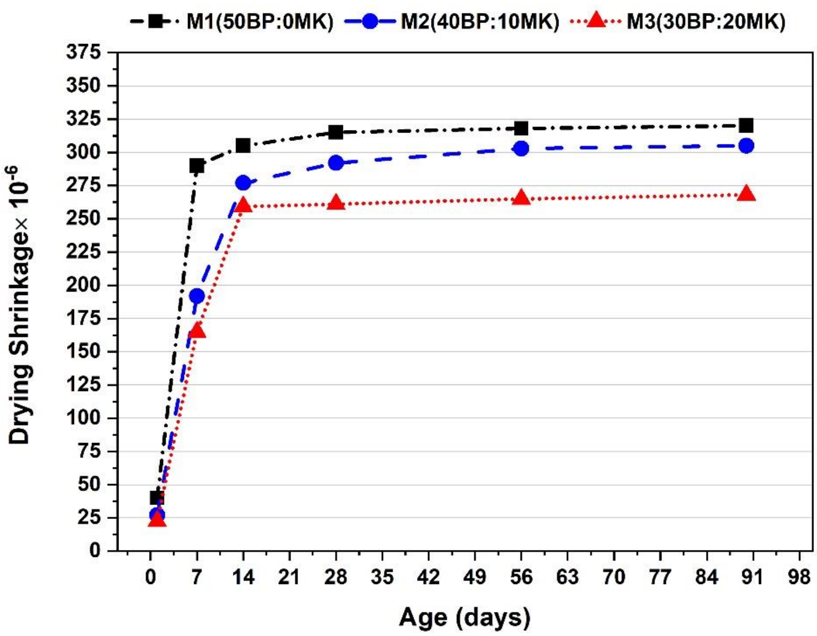

Fig. 12. Drying shrinkage of HVBP concrete mixtures

4. CONCLUSIONS

This research aims to propose sustainable practices for recycling waste bricks and examine the feasibility of implementing these waste materials in high volume as a cement replacement in the manufacturing of concrete.

The following conclusions have been drawn from the obtained results:

- It is possible to generate high volume brick powder concrete by using a blend of 50% OPC and 50%BP as a cement binder, with excellent workability (180 mm), sufficient structural strength (34.9 MPa), and adequate modulus of rupture. Furthermore, the durability performance of this concrete is highly promising because of its low void content and minimal drying shrinkage.
- In the context of workability qualities, the addition of 10% and 20% MK negatively impacts the slump and flow table values. However, fresh concrete still possesses a high level of workability, making it suitable for use in a wide range of structural components.
- Incorporating 10% and 20% of MK into the cement binder (BP: OPC) has the advantage of decreasing the temperature of fresh concrete. Therefore, this particular form of concrete is suitable for usage in hot weather or in mass concrete applications.
- A significant impact of the inclusion MK within the HVBP concrete mixture regarding drying shrinkage. It was observed that the drying shrinkage of the reference mix has been reduced at all ages with the increase in MK content. The blended mixture of 20% MK with 30% BP and 50% OPC was the optimum binder, as low drying shrinkage is a priority concrete requirement.

In summary, the production of concrete based on high volume of waste brick powder and synergistic with metakaolin will be a potential solution toward sustainability and less footprint impact. This green concrete meets the mechanical requirements of many civil engineering projects.

For more comprehensive analysis, it is recommended to conduct further research in order to ascertain the creep behavior, fire resistance, and life cycle assurance in aggressive environment of this HVBP concrete.

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