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Novel approach to improve nano green mortar behaviour using nano-paper waste with nano-metakaolin

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Abstract. Treatment of solid waste building materials is a crucial method of disposal and an area of ongoing research. New standards for the treatment of solid waste building materials are necessary due to multisource features, huge quantities, and complicated compositions of solid waste. In this research, sustainable nanomaterial mixtures containing nano-paper waste (NPW) and nano-metakaolin (NMK) were used as a substitute for Portland cement. Portland cement was replaced with different ratios of NPW and NMK (0%, 4%, 8%, and 12% by weight of cement) while the cement-to-water ratio remained constant at 0.4 in all mortar mixtures. The fresh properties had a positive effect on them, and with the increase in the percentage of replacement, the fresh properties decreased. The results of compressive strength at 7 and 28 days and flexural strength at 28 days show that the nanomaterials improved the strength, but the results of NMK were better than those of NPW. The best replacement rate was 8%, followed by 4%, and finally 12% for both materials. The combination of NMK and NPW as a replacement (12% NMK + 12% NPW) showed less shrinkage than the others because of the high pozzolanic reactivity of the nanomaterials. The combination of NMK and NPW improved the microstructure by increasing the hydration volume and lowering the water in the cement matrix, as clearly observed in the C-S-H decomposition.

Graphical abstract.

Keywords: mechanical properties; microstructure; nano green mortar; nano-metakaolin; nano-paper waste; short-term dry shrinkage

1. Introduction

The principal active components of cementitious composites commonly utilised in modern construction are Portland cement-based binders. Cement manufacturing produces large amounts of carbon dioxide (CO_2), which is a major greenhouse gas causing global warming (Tayeh *et al.* 2020, Jaradat *et al.* 2021, Tahwia *et al.* 2021, Tayeh and Magbool 2021).

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In recent years, solid waste from the building industry has grown increasingly popular as a cement substitute because of its environmental friendliness, abundance, low energy consumption, zero cost, and high binding characteristics, which meet the requirements for construction material. Reusing these waste goods helps save natural resources, promote sustainability and prevent landfill disposal (Amaral *et al.* 2020, Samadi *et al.* 2020). Despite the use of different industrial wastes as a cement substitute, some essential technical issues remain to be addressed, including cost, stability, durability, environ-mental responsiveness, and sustainability (Mohammadhosseini *et al.* 2019, Edalat-Behbahani *et al.* 2021). More than 450 million tons of paper are produced globally each year, with demand expected to approach 500 million tons by the end of2024 (Ali *et al.* 2013). The pollution created by discarded paper and paper products has

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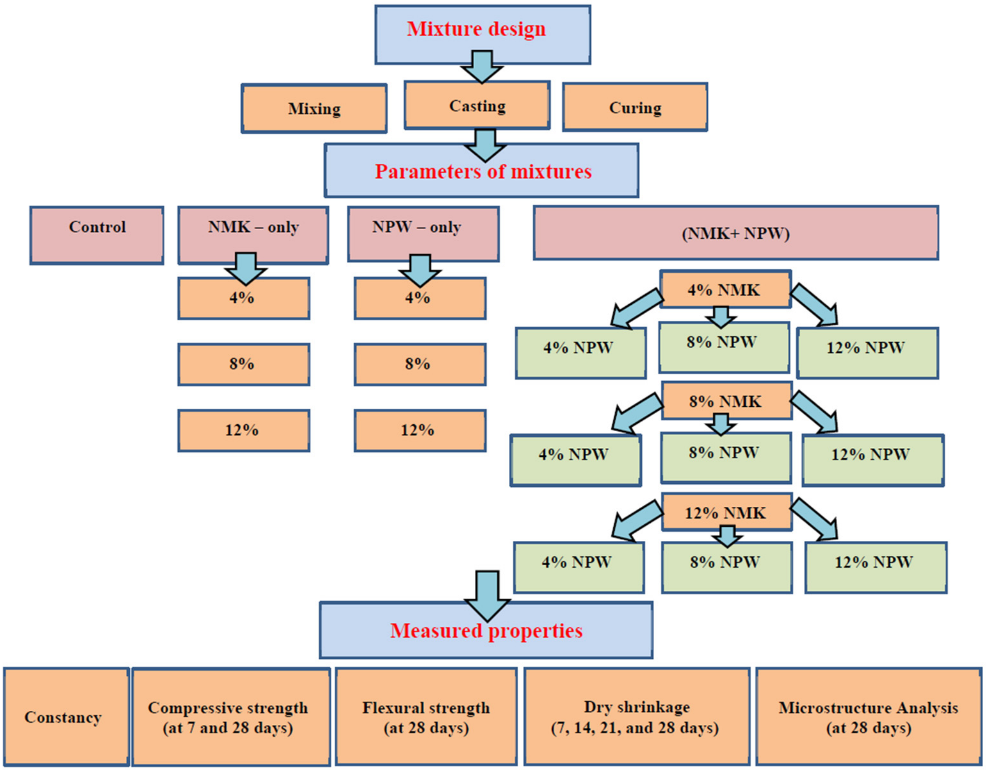

Fig. 1 Details of the carried out experimental programme

a substantial environmental impact. Paper and paperboard have accounted for the majority of paper products used globally in recent years (Kaufman and Themelis 2009, Staley and Barlaz 2009). Most waste papers are thrown away in landfills. Some are burned, resulting in air, water, and land pollution. The recycling of waste has not been able to keep up with the manufacturing of waste paper. Waste paper is a unique recycling opportunity because it may be utilised as a construction material (Wallbaum and Buerkin 2003). As a result, employing waste paper for building not only could maintain waste paper recycling up to date with its production but also lessen the demand on world natural resources (Akinwumi *et al*. 2014). Nano-metakaolin (NMK) is an excellent nano-material recently produced and used in mortar. It is more suitable than other nanoparticles, such as nano-SiO_2 and nano-$CaCO_3$, for mortar alteration (Shanmugavadivu *et al*. 2014). Many studies have examined the fundamental characteristics of NMK and the effect of this material on the properties of mortar since the feasibility of employing NMK in the mortar was discovered (Morsy *et al*. 2012, Fan *et al*. 2016). Nanotechnology has aroused considerable scientific interest in recent years because of the new conceivable uses of nanoparticles (10^{-9} m). Nanoparticles may possess considerably superior properties over standard grain-size materials with the same chemical makeup. These materials can be used to produce a mortar that is durable, strong, and easy to work with (Monteiro *et al*. 2009, Shebl *et al*. 2009).

The present study aims to provide an overview of the use of NMK with nano-paper waste (NPW) in mortar. Firstly, the chemical properties of NMK and NPW are discussed. Then, the microstructure and fresh, mechanical, and physical properties of mortar made with NMK and NPW are thoroughly examined (Fig. 1). The key results and recommendations are described in detail, which will aid future research on the subject.

2. Research importance

- The significance of this research lies in the investigation of sustainable materials, such as NMK and NPW, both of which have received little attention previously.
- To use Nano green mortars, NMK and NPW as a partial substitute for cement mass Nano green mortar (NGM).
- NGM was prepared by combining varying quantities of NMK and NPW, resulting in compressive strength of 63.7 MPa after 28 days.
- The impact of NMK and NPW on the microstructure of NGM and its new and mechanical characteristics were studied.

3. Experimental work

3.1 Materials

Ordinary Portland cement (OPC), ASTM C-150 Type I (Helwan Cement Company, Egypt) (ASTM), was used in this investigation. The oxide compositions of OPC, NPW, and NMK are shown in Fig. 2. In the mortar preparation, commercial local sand was used as a fine aggregate, and tab

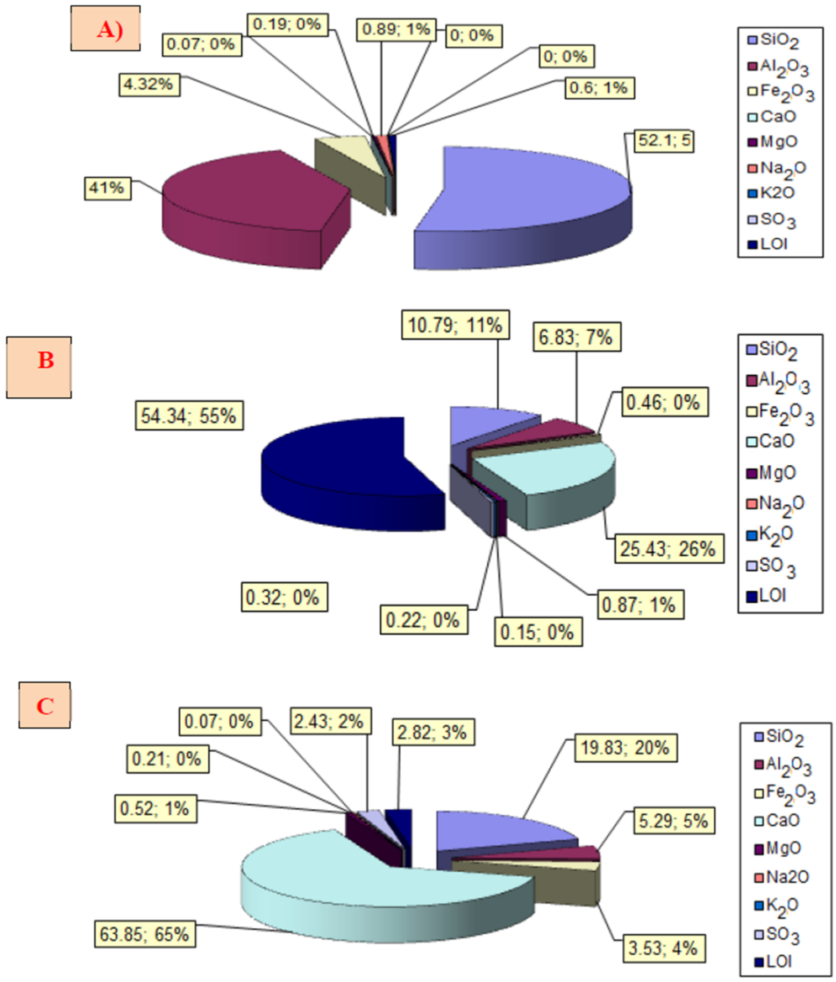

Fig. 2 Chemical composition of cement (A); nano-metakaolin (B); and nano-paper waste (C) via X-ray fluorescence

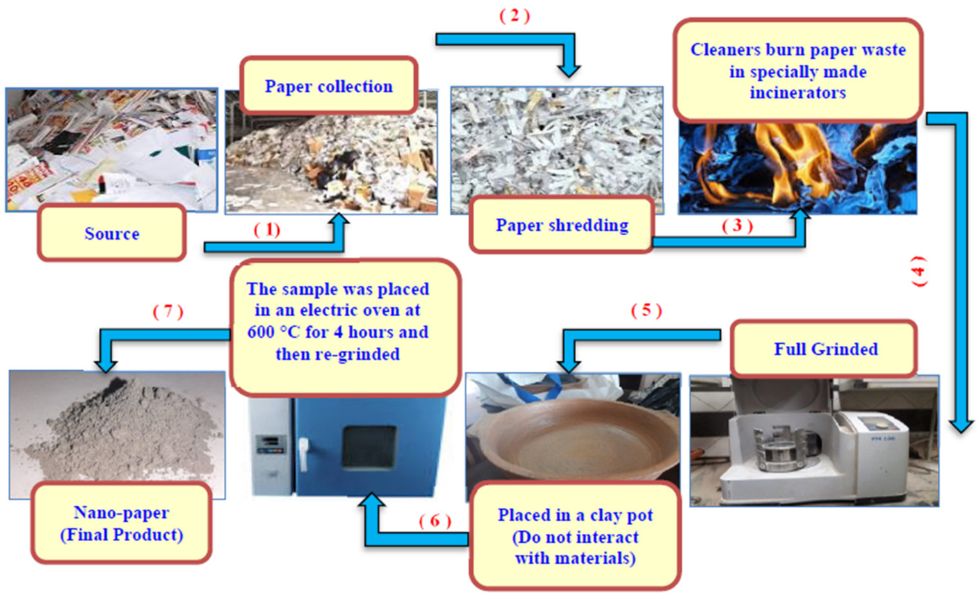

Fig. 3 Schematic of NPW production

water was used; the specifications of sand and water followed the British standards BS EN 196-1 (BSI 2005) and BS EN1008 (EN 2002), respectively.

Fig. 4 Sample grinding machine

3.2 Synthesis of Nanomaterials

3.2.1 Synthesis of NPW

Nano-paper (NP) was manufactured in a homemade way. Firstly, paper waste (PW) free of any contaminants was collected from various places. Secondly, the paper was cut into small pieces to make it easier to handle. Thirdly, paper waste was burned in specially made incinerators by cleaners (hygiene authority), producing fine ash, which must be converted to NPW and used in mortar through exposure to heat at 600 °C for 4 h. (Fig. 3). The NPW had a particle size range of 7.47–21.97 nm with an average of 12.71 nm.

3.2.2 Synthesis of NMK:

Nano-kaolin (NK) with a particle size range of 0.05:0.13 nm and an average of 0.088 nm was purchased from the Middle East Mining Investments Company (Cairo, Egypt). The main mineral phases of raw NK are kaolinite, illite, and quartz, whereas NMK comprises illite and quartz. Fig. 4 shows the grinding machine after heat treatment of raw NK at 750°C, resulting in the loss of the crystalline structure of kaolinite and the establishment of an amorphous structure.

3.3 Mixture proportions

A control mixture was developed to create a fair cement mortar consistency with a cement–sand–water ratio of 1:3:0.4. However, three mixtures of Group I: NMK-4%, NMK-8%, and NMK-12% were prepared with partial replacement ratios of 4%, 8% and 12% of cement by NMK. Another three mixtures of Group II: NPW-4%, NPW-8%, and NPW-12% were prepared to compare the effect of using NPW containing 4%, 8%, and 12% of NPW as a replacement ratio of cement. Finally, nine mixtures of Group III: 4% NMK+4% NPW, 4% NMK+8% NPW, 4% NMK+12% NPW, 8% NMK+4% NPW, 8% NMK+8% NPW, 8% NMK+12% NPW, 12% NMK+4% NPW, 12% NMK+8% NPW and 12% NMK+12% NPW of cement with partial replacement ratios of 4%, 8% and 12% were prepared. Sixteen cement mortars containing replacement ratios of cement by NMK, NPW, and NMK with NPW were designed (Table 1).

3.4 Testing procedure

The mechanical characteristics of cement mortar were determined and compared. The mortars were divided into three groups (control, Group I with NMK replacement ratios, Group II with a replacement ratio of NPW, and Group III with a replacement ratio of NMK with NPW). The ASTM C192-02 standard was followed for making and curing mortar test specimens in the laboratory (Standard 2013). The consistency of the fresh mortars was determined by 48 tests utilising the flow table method, which was utilised to compute the flow of mortar following the ASTM C1437-15 standard (Standard 2007). Ninety-six cubes samples with dimensions of 50 mm × 50 mm × 50 mm were prepared and cured to perform compressive tests after 7 and

Table 1 Cement mortar chpgomponents (kg/m3)

	Sample	Cement	Sand	Water	NMK	NPW
	C -0.0%	540.7	1622.03	216.3	0.00	0.00
Group I	NMK -4%	519.1	1622.03	216.3	21.6	0.00
	NMK -8%	497.4	1622.03	216.3	43.3	0.00
	NMK -12%	475.8	1622.03	216.3	64.8	0.00
Group II	NPW - 4%	519.1	1622.03	216.3	0.00	21.6
	NPW - 8%	497.4	1622.03	216.3	0.00	43.3
	NPW - 12%	475.8	1622.03	216.3	0.00	64.8
Group III	4% NMK + 4% NPW	497.5	1622.03	216.3	21.6	21.6
	4% NMK + 8% NPW	475.8	1622.03	216.3	21.6	43.3
	4% NMK + 12% NPW	454.3	1622.03	216.3	21.6	64.8
	8% NMK + 4% NPW	475.8	1622.03	216.3	43.3	21.6
	8% NMK + 8% NPW	454.1	1622.03	216.3	43.3	43.3
	8% NMK + 12% NPW	432.6	1622.03	216.3	43.3	64.8
	12% NMK + 4% NPW	454.3	1622.03	216.3	64.8	21.6
	12% NMK + 8% NPW	432.6	1622.03	216.3	64.8	43.3
	12% NMK + 12% NPW	411.1	1622.03	216.3	64.8	64.8

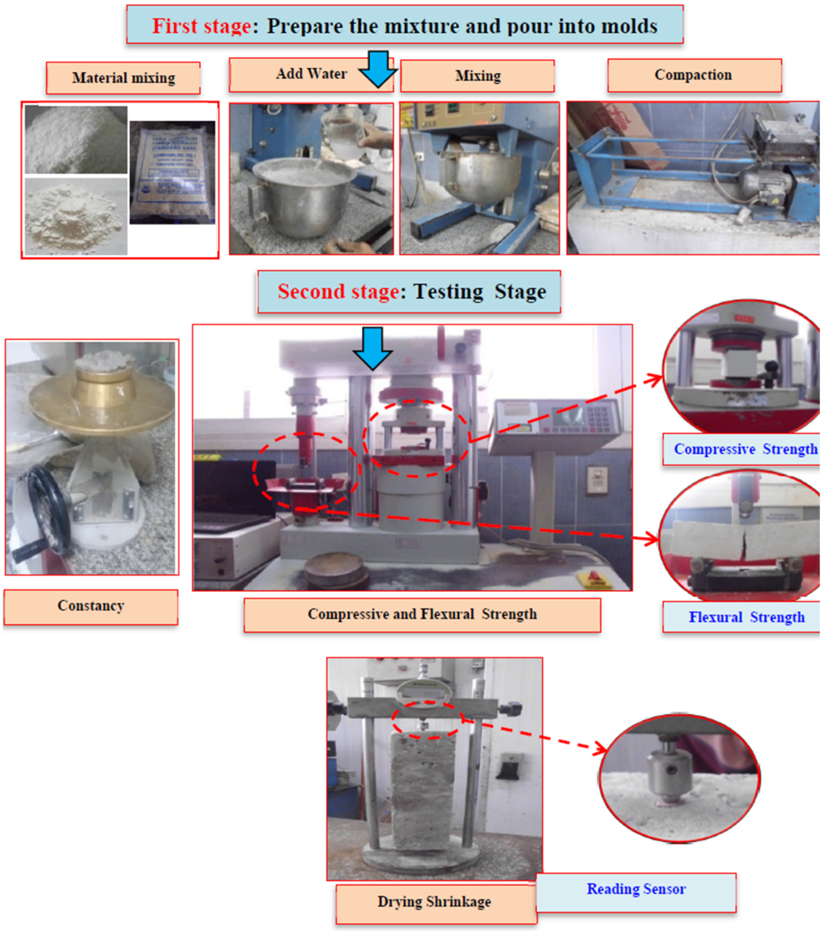

Fig. 5 Scheme of the mixing and testing phases

Table 2 Mechanical results of NMK, NPW, and NMK with NPW mixtures

Sample		Constancy (mm)	Compressive strength at 28 days (MPa)	Compressive strength at 28 days (MPa)	Flexural strength at 28 days (MPa)
C -0.0%		150	39.2	53.1	8.55
Group I	NMK -4%	148	45.1	59.7	10.56
	NMK -8%	146	46.2	61.3	11.04
	NMK -12%	143	43.3	58.1	10.13
Group II	NMK -4%	147	40.0	54.7	8.82
	NMK -8%	144	40.8	56.5	9.14
	NMK -12%	142	38.1	51.4	8.25
Group III	4% NMK + 4% NPW	146	43.4	58.4	10.23
	4% NMK + 8% NPW	143	46.3	60.2	10.82
	4% NMK + 12% NPW	141	41.2	57.1	9.54
	8% NMK + 4% NPW	142	47.4	61.4	11.10
	8% NMK + 8% NPW	140	48.0	63.7	11.57
	8% NMK + 12% NPW	137	45.2	60.1	10.77
	12% NMK + 4% NPW	136	42.0	57.4	9.92
	12% NMK + 8% NPW	134	44.4	58.8	10.43
	12% NMK + 12% NPW	131	41.0	56.6	9.21
Standard deviation		5.25	3.018	3.18	0.99

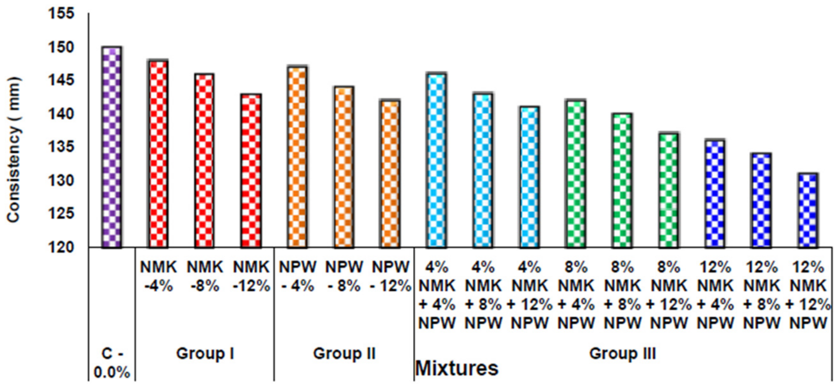

Fig. 6 Constancy values for all mixtures

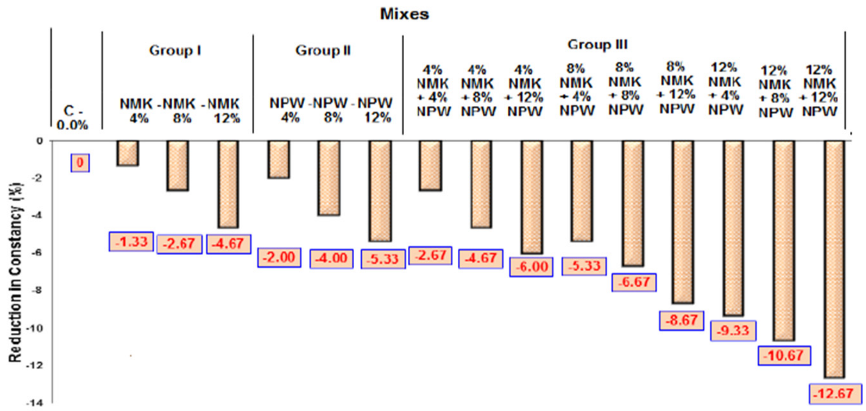

Fig. 7 Reduction in constancy (%) for all mixtures

28 days, whereas flexural strength tests were performed on 48 prismatic specimens of 40 mm × 40 mm × 160 mm using a three-point testing system and tested at 28 days following the BS EN 196-1 standard (EN 2005). Short-term drying shrinkage tests were performed on mortar samples provided following ASTM C 596-01. At various ages, three prismatic samples were measured to be 25 mm × 25 mm × 285 mm at 7, 14, 21, and 28 days. Microstructure analysis was performed to explore the effect of replacement materials on the performance parameters of the mortars via transmission electron microscopy (TEM), as shown in Fig. 5.

4. Results and discussion

The physical and mechanical qualities of NMK, NPW, and NMK with NPW were studied. Table 2 summarises the results of the experiment, including constancy, compressive strengths at 7 and 28 days, flexural strength, and dry shrinkage.

4.1 Fresh mortar properties

Fig. 6 depicts the constancy value of all mixtures and the relationship between the constancy value and replacement ratio. Constancy ranged from 150 to 131 mm in all mixtures with NMK only, NPW only, and NMK with NPW. The constancy value decreased as replacement percentages increased. Constancy values for the C-0.0%, NMK-4%, NMK-8% and NMK-12% mixtures were 150, 148, 146 and 143 mm, respectively. The group II values for the NPW-4%, NPW-8% and NPW-12% mixtures were 147, 144 and 142 mm, respectively. Finally, the values of the third group range from 146 mm to 131 mm. With the increase in substitution ratio, the decrease in the constancy rate for all mixtures increased, and NPW was affected by the drop more than NMK (Fig. 7). This result was more evident in the case of combining Nano-paper with NMK in the third group, especially with the increase in replacement rate, which agrees with previous studies (Morsy *et al*. 2014, Azar *et al*. 2019, Xie *et al*. 2020). Table 2 shows the standard deviation.

4.2 Mechanical properties

Compressive and flexural strength improved when the nanoparticles were added to the mortar. Compared with the reference mortar mix, the NPW and NMK mixtures showed higher compressive strength (Fig. 8) (Xiaoyu *et al*. 2018, Azar *et al*. 2019, Raheem *et al*. 2021).

Firstly, when NMK was added at a low replacement rate of 4%, compressive strength slightly increased by 12.43% at all ages when compared with the reference mortar mix. When the percentage of replacement was increased to

Table 3 Results of Short-term drying shrinkage for NMK, NPW, and NMK with NPW mixtures

Sample		Constancy (mm)	Compressive strength at 28 days (MPa)	Compressive strength at 28 days (MPa)	Flexural strength at 28 days (MPa)
C -0.0%		302.3	621.2	931.1	1248.4
Group I	299.3	610.6	905.5	1206.3	10.56
	298.8	608.1	903.4	1182.6	11.04
	292.7	587.4	878.7	1170.4	10.13
Group II	299.5	610.6	910.4	1217.3	8.82
	298.1	611.6	909.4	1215.4	9.14
	296.2	604.5	904.3	1211.5	8.25
Group III	295.4	593.4	873.1	1170.1	10.23
	287.4	587.5	870.4	1160.2	10.82
	281.2	575.9	855.6	1128.3	9.54
	292.4	582.4	863.1	1132.1	11.10
	290.4	575.5	861.4	1128.2	11.57
	287.2	558.9	755.6	1009.3	10.77
	290.4	592.4	773.1	1015.1	9.92
	289.4	581.5	760.4	1009.2	10.43
	287.2	550.9	753.6	980.3	9.21
Standard deviation		5.82	19.80	61.17	86.56

8%, the compressive strength increased by 15.44% compared with the control. When the replacement ratio was further increased to 12%, the compressive strength increased by 9.42%, which is smaller than the rate of increase achieved with replacements of 4% and 8%. Secondly, when nano-paper was added at the same previous replacement rates, the rate of increase was less than those obtained with NMK. In specific, the percentages of increase were 3.01% and 6.40% for NPW-4% and NPW-8%, respectively, except for NPW-12%, where a 3.20% decrease occurred. This result explains that the percentage of replacement is higher than the permissible rate and that dehydration shrinkage occurs in the samples, resulting in cracks, which may negatively affect the resistance. Therefore, cement replacement ratios were maintained low to avoid this. The higher rate of replacement varies from one material to another because of the nature of the additive and the physical and chemical properties. Finally, when NMK was added with NPW, the first group (4% NMK + (4%, 8%, 12%) NPW) increased by 7.53% to 13.37%, the second group (8% NMK + (4%, 8%, 12%) NPW) increased by 13.18% to 19.96% and the third group (12% NMK + (4%, 8%, 12%) NPW) increased by 6.59% to 10.73%. The highest rate of increase was obtained with 8% NMK + (4%, 8%, 12%) NPW), followed by 4% NMK + (4%, 8%, 12%) NPW, and 12% NMK + (4%, 8%, 12%) NPW (Figs. 8 and 9**)**. The addition of NMK achieved a higher increase than the addition of NPW at a rate of 19.96% when compared with the control. This result can be attributed to the nature of the chemical composition of NMK and the presence of interacting substances that positively affect the resistance at a higher rate than NPW (Ali *et al*. 2013, Qian *et al*. 2019, Zhan *et al*. 2020). Table 2 shows the standard deviation.

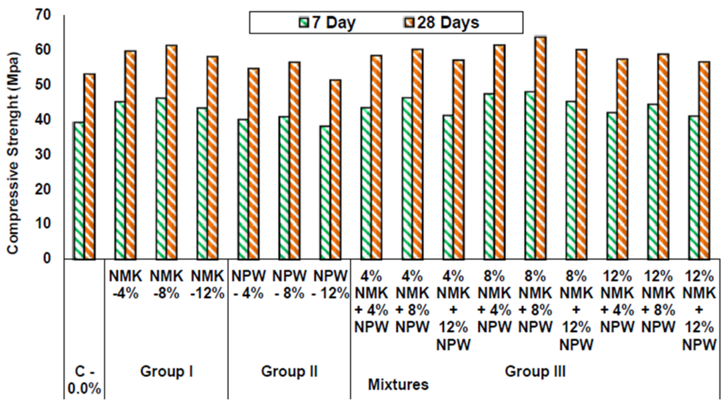

Fig. 8 Compressive strength of mortar containing NMK and NPW at 7 and 28 days

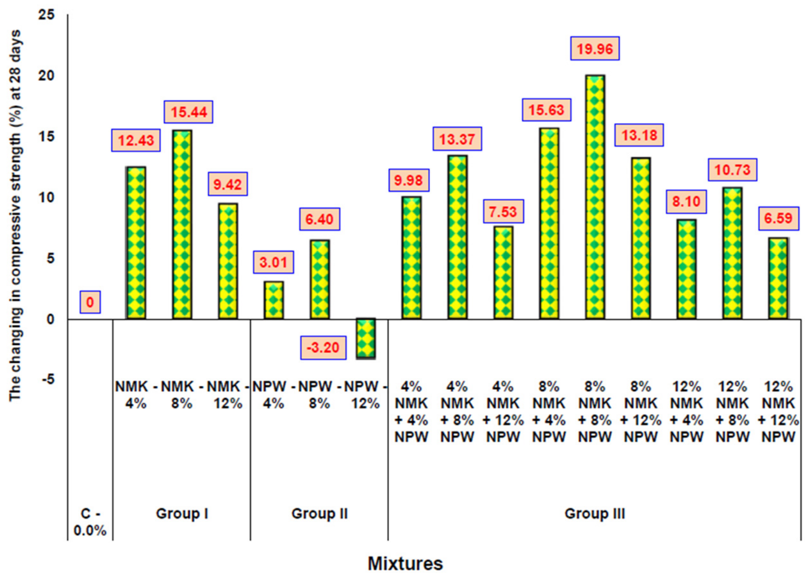

Fig. 9 Changes in compressive strength at 28 days (%)

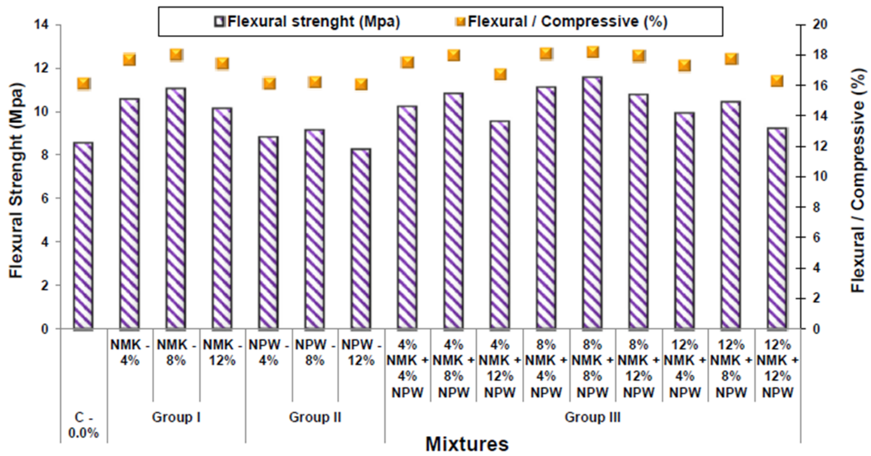

Fig. 10 Flexural strength and flexural/compressive (%) of all mixtures at 28 days

Replacement of the nanomaterial with cement increased the compressive strength, which was reflected in the flexural strength and flexural/compressive (%), as shown in Figs. 10 and 11. The increase in compressive strength increased the flexural/compressive ratio in the same trend. The addition of ultra-fine materials to mortar increased the chemical reaction and density of the mortar, which increased the resistance and improved the mechanical properties (Zhan *et al*. 2020, Pillay *et al*. 2021, Faraj *et al*. 2022).

4.3 Physical properties (Short-term dry shrinkage)

The drying shrinkage of the samples at 7, 14, 21, and 28 days is shown in Figs. 12 and 13, and the drying shrinkage decreased from 7 to 28 days as the curing age increased. This result can be ascribed to the matrix's self-desiccation and water dispersion to the exterior, which agrees with previous studies (Farzadnia *et al*. 2015, Haruehansapong *et al*. 2017). The observed dry shrinkage was nearly the same in all samples. As shown in Figs. 12 and 13, the dry shrinkage decreased in the samples with NMK at 28 days. For example, the addition of NMK-4%, NMK-8%, and NMK -12% reduced the drying shrinkage strains to 1206.3 × 10^{-6}, 1182.6 × 10^{-6}, and 1170.4 × 10^{-6} mm/mm, respectively, when compared with the control (1248.4 × 10^{-6} mm/mm). Meanwhile, the addition of NPW-4%, NPW-8%, and NPW-12% reduced the drying shrinkage strains to 1217.3 × 10^{-6}, 1215.4 × $10^{-6,}$ and 1211.5 × 10^{-6} mm/mm, respectively, when compared with the control (1248.4 × 10^{-6} mm/mm). Replacing cement with 12% NMK + (4%, 8%, 12%) NPW resulted in the lowest reduction in shrinkage at all ages, which is consistent with a prior study [32]. The highest drying shrinkage strain for the NPW-only samples was found in the samples with NPW-4%. The NMK sample recorded the lowest shrinkage rate, indicating that the NMK sample had lower shrinkage performance than the NPW sample. Table 3 shows the standard deviation.

The combination of NMK and NPW reduced drying shrinkage, which could be attributed to the lower permeability caused by the creation of higher amounts of secondary C–S–H and the filling impact of nanoparticles.

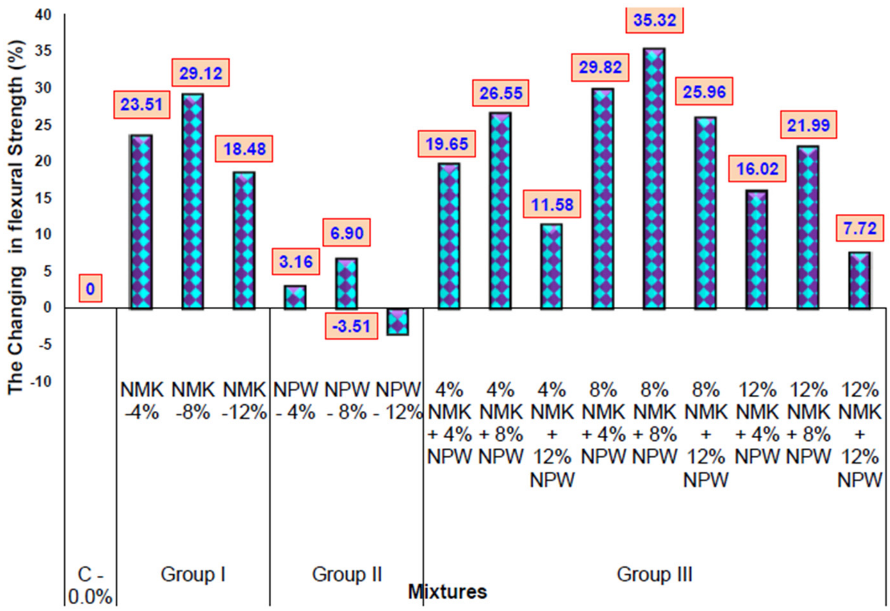

Fig. 11 Changes in flexural strength (%) at 28 days

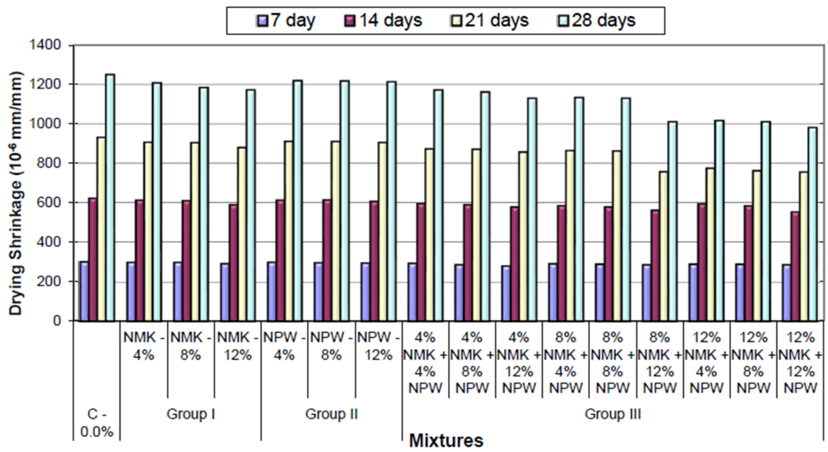

Fig. 12 Dry shrinkage of all mixtures at 7, 14, 21, and 28 days

Moreover, the reduction in the dry shrinkage of NPW may be addressed differently and more similarly to NMK when NMK was combined with NPW in the samples (Itim *et al*. 2011, Mastronardi *et al*. 2015, Ahmed *et al*. 2022).

4.4 Analysis of microstructure

4.4.1 Characterisation of NMK and NPW by transmission electron microscopy

Chemical information and images of the nanomaterials with atomic-scale spatial resolution were obtained using transmission electron microscopy (TEM). When an electron beam interacts with a thin foil object, incoming light is turned into elastically or inelastically scattered electrons. The distance between the objective lens, the specimen, and the picture plane is multiplied by the lens, as shown in Fig. 14. TEM has advantages in terms of spatial precision, analysis and efficiency. TEM uses powerful electrons to convey information about the morphologic, compositional, and crystallographic properties of nanoparticles. TEM is based on optical microscopy theory. Instead of using optical lenses, electromagnetic lenses are utilised, and images are displayed on a screen rather than through an eyepiece. Strong magnification and knowledge of compound and element structures are two advantages of TEM (Winey *et al*. 2014, Inkson 2016, Tang and Yang 2017, Mansi *et al*. 2022). NMK and NPW are composed of clusters of nanoparticle crystals (NMK is 0.088 nm and NPW is 12.71 nm in size), as shown in Figs. 13 and 14. Figs. 15(b) and 16(b) display the selected area electron diffraction image showing the crystalline properties of NMK and NPW.

4.4.2 Scanning Electron Microscopy (SEM) of nano-mortar

Scanning electron microscopy revealed the homogeneity of the hardened mortar microstructure, which reflects the pressure resistance value of the mixtures in order as follows: 8% NMK + 8% NPW, NMK-8%, NPW-8%, and C-0.0%. Nanoparticle powder acts as a filler or binder that enhances the performance of the interfacial transition zone

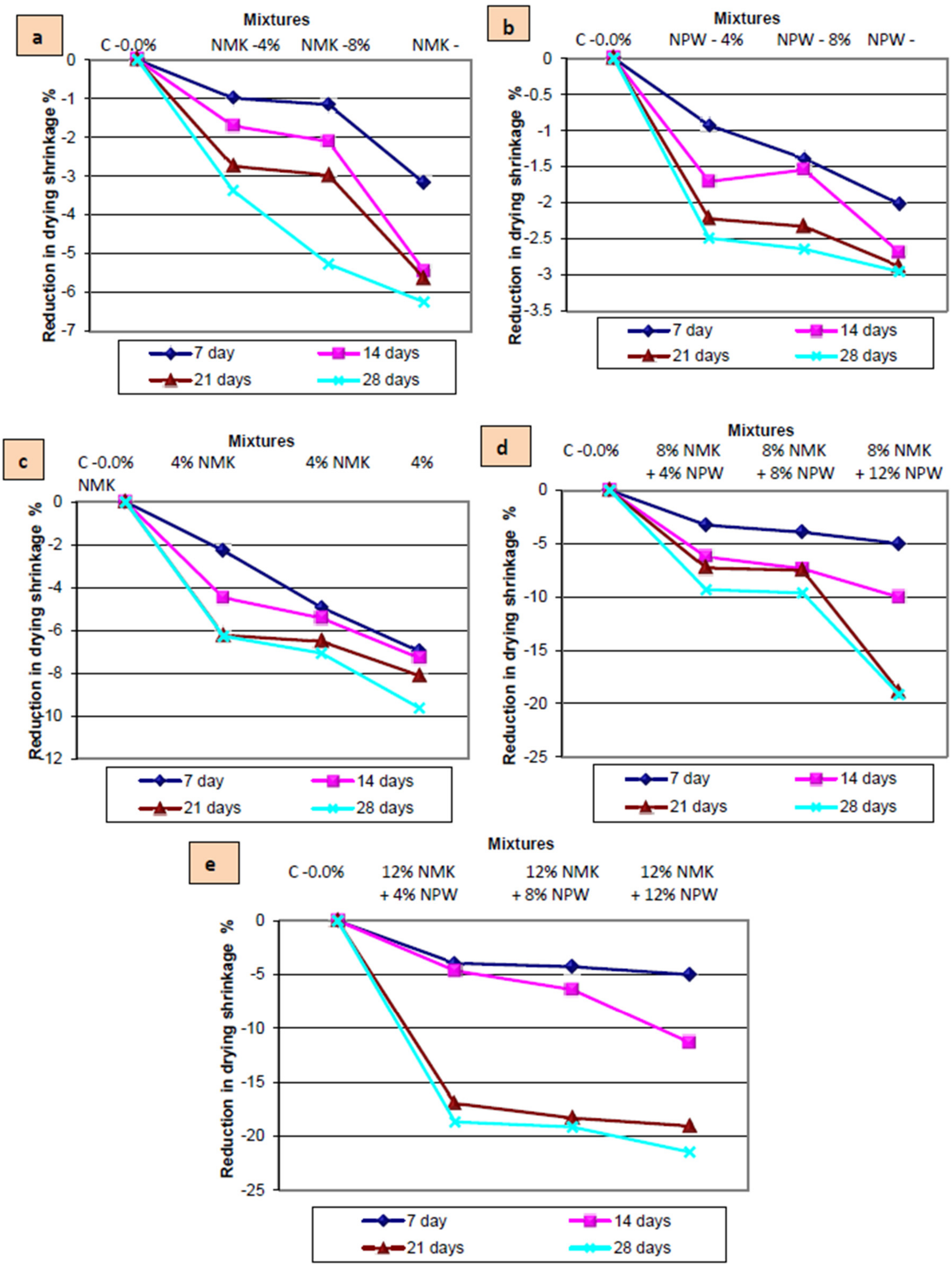

Fig. 13 (a), (b), (c), (d), (e) Dry shrinkage reduction in the samples with NMK only, NPW only, 4% NMK + (4%, 8%, 12%) NPW, 8% NMK + (4%, 8%, 12%) NPW and 12% NMK + (4%, 8%, 12%) NPW at 7, 14, 21 and 28 days

between the cement matrix and the aggregate and the inclusive quality of the cement mortar matrix (Paul *et al.* 2018, Ahmad *et al.* 2021, Hosan *et al.* 2021). In addition, as shown in Fig. 17, the homogeneous structure of nanoparticle powder allowed the creation of similar products with a better microstructure than conventional mortar without nanomaterials (Al-Rifaie and Ahmed 2016, Sumesh *et al.* 2017, Xiao *et al.* 2019, Tayeh *et al.* 2021a, b).

4.4.3 Dispersion of carbon nanomaterials in cement composites

The dispersion of nanoparticles in cement composite is highly challenging. This force forms agglomerations and is

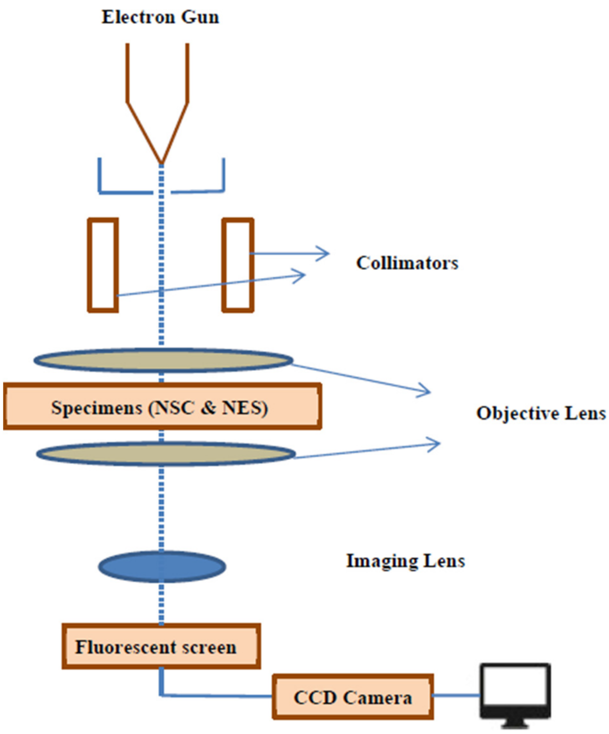

Fig. 14 Working principle of TEM

challenging to disentangle (Yazdanbakhsh *et al*. 2010). In certain regions of materials with numerous cavities, as shown in Fig. 8, a weak interfacial bond exists between the CNFs and matrix. (Adu Al-Rub *et al*. 2012) conducted a study on the impact of length on dispersion and the significance of nanomaterial length that was described above. Cement particles are huge in comparison to nanoparticles. The difference in size causes problems with size compatibility, because cement grains prevent the penetration of nanomaterials. As a result, some locations contain higher concentrations of nanomaterials, increasing the likelihood of clumping and poor dispersion (Abu Al-Rub *et al*. 2012). Additionally, insufficient dispersion creates places that are not strengthened, which promotes the spread of cracks. Inversely, inadequate dispersion can reduce the tensile, compressive and flexural strengths of cement composites and harms their mechanical properties. As a result, dispersion is crucial to the mechanical attributes of cement composites.

4.4.3.1 Methods for measuring effective dispersion

Researchers have studied the dispersion stability of carbon nanomaterials by using a variety of techniques, including electron microscopy (transmission electron microscopy [TEM] and scanning electron microscopy

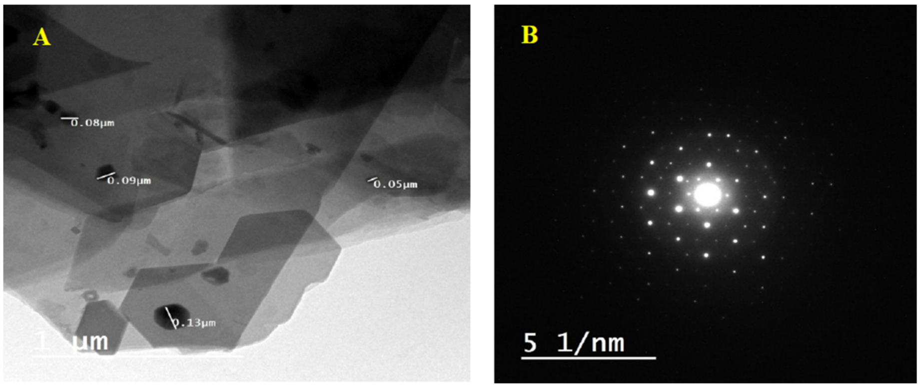

Fig. 15 (A) TEM image of nano-metakaolin; and (B) Selected area electron diffraction image showing the crystalline property of nano-metakaolin

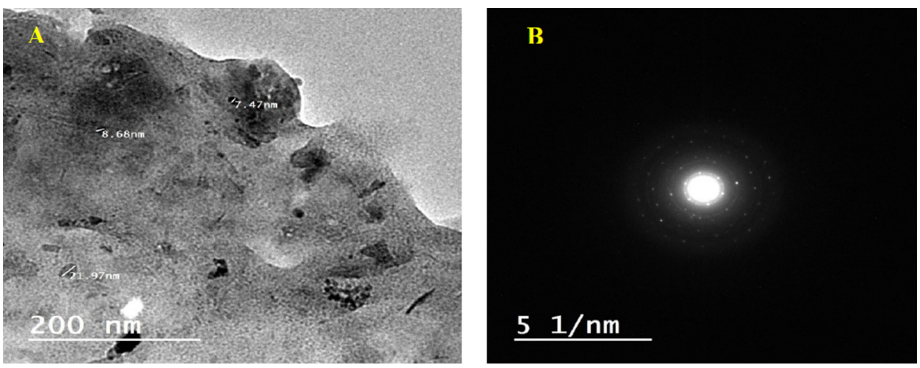

Fig. 16 (A) TEM image of nano-paper waste; and (B) selected area electron diffraction image showing the crystalline property of nano-paper waste

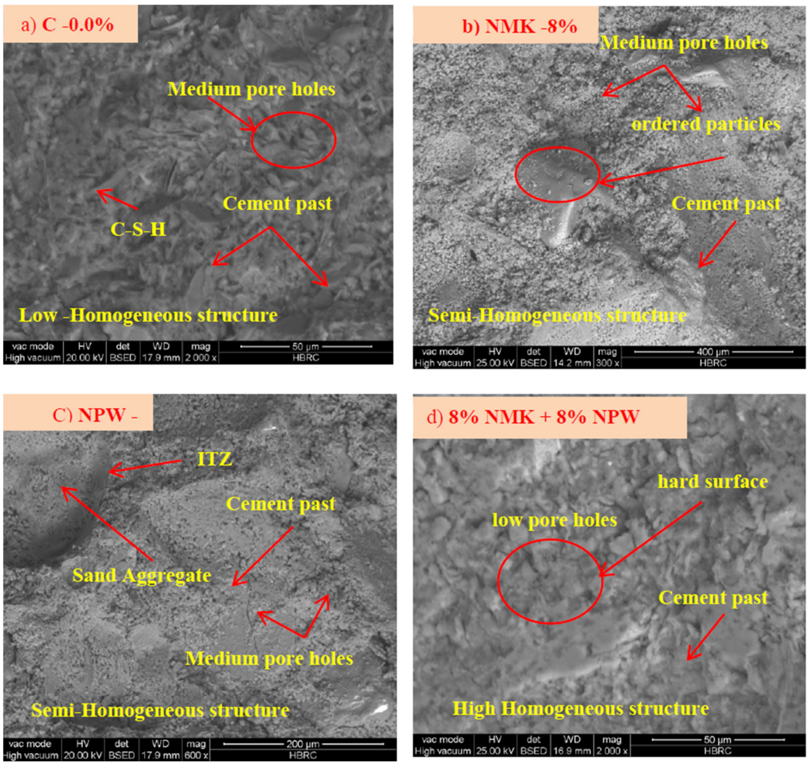

Fig. 17 SEM test for specimens (C-0.0%, NMK-8%, NPW-8%, and 8% NMK + 8% NPW)

[SEM]). SEM is the most used technique for analysing the distribution of nanomaterials in a composite (Konsta-Gdoutos *et al*. 2010, Ma *et al*. 2010, Lv *et al*. 2013). Depending on the instrument design and parameters, the SEM picture depends on surface processes and has a large depth of field. It can generate pictures that accurately depict the sample's 3D shape (Cardoza *et al*. 2022). The other methods measure dispersion in the water used to make cement paste, whereas SEM demonstrates the precise distribution of nanomaterials in the hardened matrix (Yazdanbakhsh *et al*. 2009). The wavelength of the electron beam is a key component of the TEM process and is ultimately responsible for resolution (Hornyak *et al*. 2018). The dispersion of nanomaterials has a significant effect on their performance, especially for high dosage of nanomaterials. Thus, the nano samples had an appropriate dispersion in the cement mixture on the basis of the SEM test (see Figs. 15 and 16).

5. Conclusions

This research analysed the properties of Nano green mortar composed of NPW and NMK. The following results were obtained after the mechanical characterisation and microstructure examination of the specimens as follows:

1. NPW affected the constancy more than NMK. This phenomenon was more evident in the specimen combining NPW and NMK, especially with the increase in the replacement rates.
2. The NMK-8% sample increased the compressive strength by 15.55%, which was higher than the 6.40% increase achieved by the NPW-8% sample when compared with the control. This is because the chemical composition of the materials used has a better interacting strength, which improves the compressive strength.
3. The replacement of cement with nanomaterials increased the compressive strength, which was reflected in the flexural strength, and flexural/compressive ratio, which increased the value in the same trend of the compressive strength.
4. The lowest drying shrinkage strain for the NMK + NPW samples was found in the samples with 12% NMK + 12% NPW, and the NMK sample recorded the lowest shrinkage rate, indicating that the NMK samples had lower shrinkage performance than the NPW sample.
5. NPW mortar has a slightly lower effect on mechanical behaviour than NMK mortar because of the thermal incompatibility between nanoparticles, as clearly observed in the C-S-H decomposition.
6. The homogeneous structure of nanoparticle powder allowed the creation of similar products with a better microstructure than conventional mortar without nanomaterials.

Recommendations

On the basis of the findings and conclusions of the current study, the following subjects are recommended for future research:

1. The behaviour of durability mixture with different local materials such as metakaolin and rice husk;

2. Behaviour of nano paper with structural element such as slabs, long columns and connections of frames;
3. The behaviour of geopolymer concrete using nano-paper waste with nano-metakaolin;
4. The addition of various types of fibres in geopolymer concrete and their effects on the enhancement of strength needed for nano green mortar;
5. Long-term behaviour of various nano green materials on structural elements.

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