Effect of nano clay particles on mechanical, thermal and physical behaviours of waste-glass cement mortars

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\textbf{A B S T R A C T}

Worldwide, around 2.6 billion tons of cement is produced annually. This huge size of production consumes large amounts of energy and is one of the largest contributors to carbon dioxide (CO\textsubscript{2}) release. Accordingly, there is a pressing demand to minimise the quantity of cement used in the concrete industry. The main challenge to this is to get durable concrete with less cement and within reasonable cost. The economic, environmental and engineering benefits of reusing ground waste-glass powder (WGP) as a partial cement replacement has been established, but low glass reactivity and the possible alkali–silica reaction (ASR) are a drawback. Recent advances in nano-technology have revealed that nano-sized particles such as nano clay (NC) have a high surface area to volume ratio that provides the potential for tremendous chemical reactivity, accelerating pozzolanic activity and hindering ASR. This paper presents a laboratory study of the properties of NC/WGP cement composites. The microstructure, ASR, fracture energy, compressive and flexural properties of cement mortars containing WGP as a cement replacement with and without NC are investigated and compared with plain matrix. In addition, the hydration of cement compounds was followed by differential thermal analysis (DTA), thermogravimetric analysis (TGA), and also X-ray diffraction (XRD). The results showed that incorporation of glass powder has a positive effect on the mechanical properties of cement mortars after 28 days of hydration. Also, the results revealed that the mechanical properties of the cement mortars with a hybrid combination of glass powder and NC were all higher than those of plain mortar and with glass powder after 28 days of hydration. In addition, the DTA/TGA results and XRD analysis showed a reduction in the calcium hydroxide (CH) content in mortars with glass powder and with a hybrid combination of glass powder and NC, which confirms the improvements of mechanical properties and occurrence of pozzolanic reaction after 28 days of hydration.

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1. Introduction

Although glass is a highly recyclable material, recycling of colour bottle glass causes major problems due to the high cost of cleaning and colour sorting. It is widely believed that the storage of colour bottles is cheaper than recycling them. Therefore, most colour bottle glass is regarded as a low-value product and is dispatched to landfill as waste material. Due to the fact that glass is not biodegradable, landfills do not offer an ecological solution. A potential solution providing a sustainable, ecological and economic solution to mixed-colour bottle storage would be to reuse colour waste glass in the cement and concrete industries.

The concept of using waste glass in concrete is not new; early efforts were conducted in the 1960s to use crushed waste glass as a replacement for aggregate [1]. However, these attempts were not satisfactory due to the strong reaction between the alkali in cement and the reactive silica in glass, namely alkali–silica reaction (ASR) [1,2]. In addition to ASR, using waste bottle glass limits the size and shape of coarse aggregate, as crushed bottles tend to form flaky and elongated shapes, which may negatively affect workability and reduce compressive strength. Also, most mixed-colour bottles are of different chemical composition and may be contaminated by paper, plastic labels, caps and inorganic remaining from the original content of the bottles [3]. Furthermore, using waste glass as an aggregate could decrease slump, air content, fresh unit weight, tensile and flexural strengths [4].

In the last decade, the reuse of waste glass in the cement and concrete industries has attracted many researchers due to the high disposal costs for glass and stricter environmental regulations. Cur-
Currently, several efforts have been made to overcome the limitation of ASR, focussing on reducing the particle size of the waste glass through prolonged grinding. The results of this work showed that the very fine glass powder greatly decreased ASR expansion. Furthermore, the results revealed an improvement in compressive strength, resistance to sulphate attack and chloride ion penetration with very fine glass powder (less than 100 μm).

Works of Shi et al. [5] and Schwarz et al. [6] indicated that finely ground glass powder (below 100 μm) has a pozzolanic reactivity greater than that of fly ash at low cement replacement (10–20%). When using up to 50% of waste glass as cement replacement, Chen et al. [7] found that a particle size less than 75 μm possesses cementitious capability and improves compressive strength, resistance of sulphate attack and chloride ion penetration. In another work, Corinaldesi et al. [8] used sodium–calcium glasses with particle size ranging from 36 μm to 100 μm, to study the effect of glass particle size on ASR. Their results did not detect any deleterious effect at a macroscopic level due to the reaction between cement paste and ground waste glass with particle size up to 100 μm. Also, their results showed a strong improvement in the compressive and flexural strength of the mortar, due to the positive contribution of the waste glass to the micro-structural properties. Work by Karamberi and Moutatsou [9] indicated that finely ground colour glass cullet up to 90 μm was found to increase pozzolanic activity, to improve compressive strength and to cause negligible ASR expansion. Idir et al. [10] showed that the pozzolanic activity increases with glass fineness and equivalent or superior compressive strength can be attained when using up to 40% of mixed-colour glass (less than 40 μm), compared to their reference specimen without glass.

In fact, the reusing of glass in the concrete industries is accompanied by two antagonistic behaviours depending on the size of the glass particles: ASR, which causes negative effects, and pozzolanic reaction, which improves the mechanical and physical properties of concrete. As the previous works show, the use of waste glass as a cement replacement has shown mixed results over a range of levels of replacement and particle sizes. In relevance to the requirements of ASTM C618 [11], as shown in Table 1 [3,12–16], glass has the potential to acceptably function as a cement replacement; however, proper methods must be developed to control the ASR/pozzolanic reaction and increase the glass powder reactivity.

Recent studies have shown that nano-sized particles such as nano silica, TiO₂ nanoparticles and nano clay (NC) particles have a high surface area to volume ratio that have the potential for tremendous chemical reactivity [17–21]. Nano-particles act as nuclei for cement phases, hence promoting cement hydration due to their high reactivity. Also they act as a nano-reinforcement, and filler. Thus they densify the microstructure and accelerate pozzolanic activity [18,21,22]. Therefore, using nano-particles to increase the pozzolanic activity of waste glass powder (WGP) would be a promising approach to improving the performance of WGP and controlling the damaging effect of ASR. The literature review has shown that studies on this subject are very limited. This work investigates the hybrid effect of NC particles and WGP on the ASR, microstructure, hydration of cement compounds, fracture energy, flexural and compressive properties of cement mortars.

In this study, green WGP with particle obtained from alcohol bottles (5%, 20%, 30 and 50% of total cement weight) and NC particles (2.5 wt%) were used as a partial replacement for cement. In order to characterise these developed composites, a series of tests were conducted. These consisted of a study of the ASR, microstructural properties, fracture energy, pozzolanic activity, compressive and flexural performance. In addition, the hydration of the cement matrices was followed by differential thermal analysis (DTA), thermogravimetric analysis (TGA), and X-ray diffraction (XRD).

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<tbody>
<tr>
<td>SiO₂</td>
<td>63.0–80.5</td>
<td>21.78</td>
<td>11.8–35</td>
<td>92</td>
</tr>
<tr>
<td>Al₂O₃</td>
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<td>6.56</td>
<td>2.0–12</td>
<td>0.7</td>
</tr>
<tr>
<td>Fe₂O₃</td>
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<td>4.13</td>
<td>0.3–22.6</td>
<td>1.2</td>
</tr>
<tr>
<td>CaO</td>
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<td>60.12</td>
<td>39.6–47.5</td>
<td>0.3</td>
</tr>
<tr>
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<td>2.08</td>
<td>0.0–7.5</td>
<td>0.2</td>
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<tr>
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<tr>
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<td>0.36</td>
<td>0.2–0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>SO₃</td>
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<td>2.16</td>
<td>0.2–9.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Others</td>
<td>0.05–3.5</td>
<td>2.39</td>
<td>–</td>
<td>2</td>
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<tr>
<th>Physical and chemical properties of Closite® 30B as provided by the manufacture.</th>
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<tbody>
<tr>
<td>Physical and chemical properties</td>
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<tr>
<td>Density</td>
</tr>
<tr>
<td>Moisture content</td>
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<tr>
<td>Average size</td>
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<tr>
<td>Basal spacing, d(001)</td>
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<tr>
<td>Colour</td>
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<tr>
<td>Modifier concentration</td>
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* Milli-equivalents per 100 grams.

### 2. Materials and methods

Ordinary Portland cement (PC) was used in this study and supplied by Irish Cement Ltd. The cement was grade 42.5, with a specific gravity of 3.15 g/cm³. Sand with a particle size up to 1.18 mm and a specific gravity of 2.65 g/cm³ was obtained from a local supplier in Ireland. The clay used in this study, Closite® 30B, is commercially available from Southern Clay Products Inc., USA. This is an organically modified montmorillonite with quaternary ammonium salt, which has an initial d-space of 18.5 Å. The physical and chemical properties of the Closite® 30B provided by the manufacture are listed in Table 2. Scanning electron microscopy (SEM) micrograph of Closite® 30B particles is shown in Fig. 1. It can be seen that the particles consist mainly of fine ball-milled particles with an irregular microstructure and an average particle size of 6 μm.

The WGP used in this study was having particle size up to 75 μm and specific surface (Blaine) of 320 m²/kg. This is accomplished by crushing and grinding the glass in a ball mill in the laboratory and by sieving the ground glass to the desired particle size namely 75 μm. Table 3 shows the chemical composition of green WGP used in this work. SEM examinations indicate that the ground WGP consists

Fig. 1. SEM micrograph of Closite® 30B.
mainly of fine angular particles with a narrow particle size range, as shown in Fig. 2. Particle size analysis of the WGP was carried out using a Malvern Mastersizer S (Malvern Ltd., UK). Fig. 3 compares the particle size distribution of the PC with WGP obtained from the grinding process. It shows that in the present technique WGP contains about 45% of particles smaller than 10 μm, while PC contains about 50% of particles smaller than 10 μm.

Organically modified montmorillonite particles have a relatively higher surface area per unit volume and are difficult to mix at the same time with water, cement, and sand. Hence, the microstructural and mechanical properties of cement mortars reinforced with modified montmorillonite particles are considerably influenced by the mixing procedure of their constituent materials. Kuo et al. [22] have successfully used the high-shear mixing technique to incorporate organo-modified montmorillonite into the cement matrix. Therefore, this technique has been chosen to prepare cement–NC composites. Accordingly, mixing was performed as follows. The modified montmorillonite particles were mixed with total mixing water and stirred vigorously by a high speed shear mixer for 24 h at room temperature to form a well dispersed suspension solution. To prepare the cement mortar, the PC, WGP (if applicable) and sand were stirred at high speed for about 3 min. Afterwards, the total suspension solution was added slowly into the mixture and stirred for 3 min. Then, the well mixed composite was poured into moulds. After moulding, the specimens were kept in sealed conditions at a constant temperature of 20 °C until curing age was achieved (28 days). For all specimens the water/binder ratios were tested to reach a flow of 110 ± 5 to permit a medium workability of the specimens. Table 4 summarises the mix proportions used in this work.

### 3. Experimental techniques

A study of the ASR was performed in accordance with ASTM C1260 [23]. Mortar bars 25 mm × 25 mm × 100 mm in size were cast. Then, the moulds were covered carefully with plastic sheets and placed in the lab at 22 °C for 24 h. After that, the bars were placed in water at 80 °C for another 24 h to gain a reference length. They were then transferred to a solution of 1 N of NaOH at 80 °C. Readings were then taken every day for 14 days.

The DTA/TGA profiles were obtained using Stanton Redcroft DTA/TGA, UK. The samples (24–28 mg) were heated at 10 °C/min up to 1000 °C. Dry nitrogen gas was circulated within the test cell at a flow rate of 60 cm3/min.

DTA/TGA can be used to determine the amount of the pozzolanic reaction and hydration of blended cement pastes by estimating CH and calcium silicate hydrate (CSH) content [24]. This technique is more suitable for studying hydration at later stages [25]. Vedalkshmi [26], as well as Esteves [27], employed TGA/DTA to study the pozzolanic activity of mineral additions such as silica fume, fly ash and slag. Furthermore, the hydration of pozzolanic materials (such as silica fume, metakaoline, fly ash or slag) by estimating CH content has also been investigated in Refs. [28–31].

In the present work, CH exhibits a peak at about 475 °C. The area of this peak was used to determine the amount of CH by the method applied by Esteves [27]. Accordingly to calculate the CH content, a separate test was performed with pure CH to check the enthalpy of this compound. Thus, the amount of CH in the system was derived from Eq. (1):

\[
CH \ (\text{wt%}) = k \cdot A
\]  

(1)

where CH is the wt% of calcium hydroxide in the sample, \(k\) is the calibration constant obtained from the measurement of the pure CH (\(k = 8.11 \times 10^{-4}\)) and \(A\) is the peak area taken from the DTA profile in μV.

When using the TGA technique to estimate the content of CH, the method does not require any calibration procedure. Thus, the CH content was estimated directly from the weight loss measured from the TGA curve between the initial and final temperatures of the corresponding TGA peak [25–27].

In order to study microstructure, SEM was applied to characterise the microstructure of composites’ fracture surfaces using a
Table 5  
Mixture proportions for lime test (by weight percent).  

<table>
<thead>
<tr>
<th>Batches</th>
<th>Lime</th>
<th>WGP</th>
<th>NC</th>
<th>Sand</th>
<th>Water/lime + WGP (or NC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWGP</td>
<td>9</td>
<td>18</td>
<td>0</td>
<td>73</td>
<td>85</td>
</tr>
<tr>
<td>LNC</td>
<td>9</td>
<td>0</td>
<td>18</td>
<td>73</td>
<td>185</td>
</tr>
</tbody>
</table>

SEM machine model Hitachi S-3000N VP in secondary electron (SE) mode, operated at around 8 and 15 kV. The samples used for SEM imaging were slices taken from the same specimens used for the flexural test.

XRD (Bruker AXS D8 Advance, USA) analysis with Cu-Kα radiation and a graphite monochromatic with a current of 40 kV and a voltage of 40 mV were used with diffraction intensity in the range of 10–50° (2θ-angle range).

For the three-point flexural test, specimens of 40 mm × 40 mm × 160 mm size were prepared in accordance with ASTM C348 [32]. Flexural strength was obtained using the Zwick machine. This machine is equipped with a 50 kN load cell and attached to a computer interface with TestXpert 2 version 2.1 software for data acquisition. Three point bending tests on notched beams were performed to evaluate the fracture energy in accordance with RILEM 50-FMC [33]. All specimens were tested at room temperature with a cross-head speed of 1 mm/min. For the compressive test, specimens of 50 mm × 50 mm × 50 mm size were prepared in accordance with ASTM C109 [34]. Both flexural and compressive property values were obtained by averaging the measurements of at least three samples.

In order to study the pozzolanic activity of the WGP and NC, a lime test was conducted following ASTM C593 [35]. The mixture proportions are given in Table 5.

The water was adjusted to achieve a flow of 75% consistency through a flow table test. The mixture was cast in 50 mm cube moulds, wrapped in wet burlap, sealed by a plastic bag, and cured at 54°C in an oven.

Compressive strength tests were carried out after curing for 7 days at 54°C and after an additional 21 days curing at 23°C in water to monitor the long-term strength gain. As recommended by ASTM C593, a satisfactory pozzolanic material should have a minimum compressive strength of 4.1 MPa when mixed with lime after 7 days curing at 54°C and after an additional 21 days curing at 23°C in water.

4. Results and discussion

4.1. Mechanical properties

The results obtained through the present work on the utilisation of WGP/NC as cement replacement on the mechanical properties of mortars, can be summarised as follows.

4.1.1. Compressive strength

Fig. 4 compares the compressive strength of mortars (at 28 days of hydration) WGP/NC with WGP specimens; apparent improvement in compressive strength compared to the control specimen is reported. The compressive strength increases by increasing the glass content up to 20%, after which it slightly decreases. Evidently, incorporating NC particles has a positive effect on the compressive strength. Moreover, the increases in compressive strength for NWG5, NWG30 and NWG50 were 11%, 22% and 8%, respectively compared to the control specimen. NCWGP20 samples reveal the highest compressive strength, with a 28% increase in compressive strength compared to the control specimen. This increase indicates that the hybrid incorporation of NC particles and finely ground WGP greatly improves the mechanical performance of the cement matrix.

4.1.2. Flexural strength

The flexural strength behaves similarly to the compressive strength. Fig. 5 shows that the incorporation of WGP improves the flexural strength compared to the control specimen. The addition of NC introduces further improvement to the flexural strength of WGP mortars. Fig. 5 exhibits the increase in flexural strength for mixes NCWGP5, NCWGP20, NCWGP30 and NCWGP50 (5%, 14%, 26% and 29%, respectively), compared to the control specimen. Mix NCWGP20 revealed the highest flexural strength followed by mix NCWGP30, which confirms the similarity between compressive and flexural strength.

4.1.3. Fracture energy

Fig. 6 exhibits the variation of the fracture energy of mortars versus waste glass content percent for different specimens. It can be seen that the incorporation of WGP has a positive effect on fracture energy, which increased with increasing glass content. The incorporation of NC significantly improves the fracture energy of mortars compared to the control specimen. The increases in fracture energy for NCWGP5, NCWGP20 and NCWGP30 were 57%, 67% and 82%, respectively, compared to the control specimen. Mix NCWGP50, which contained 50 wt% WGP and 2.5 wt% NC particles, shows the highest fracture energy, recording an increase in fracture energy of 123% compared to the control specimen. This increase indicates a greater energy adsorption in NC/WGP cement composites.

![Fig. 4. 28-Day compressive strength of target mortars.](image)

![Fig. 5. 28-Day flexural strength of target mortars.](image)
As the above results show then, the NC/WGP combination showed the best results in terms of fracture energy, flexural and compressive strength. It seems that NC behaves not only as a filler to refine microstructure, but also as an activator to accelerate the pozzolanic reaction; this is due to the large and highly reactive surface of nano particles [19,36,37]. These results are further reinforced by SEM micrographs, XRD patterns and DTA/TGA of the cement mortars after 28 days of hydration. In fact, the improvements in the properties of hardened cement composites due to the addition of NC particles can be explained by two mechanisms. The first is the chemical effect, which works on two levels [18]:

- accelerating the dissolution of C3S and rapid formation of the CSH phase in the cement paste; and
- the pozzolanic reaction of silica with CH generates additional CSH gel in the final stages.

The second mechanism is the physical effect; nano clay particles can fill the remaining voids in young and partially hydrated cement paste, which leads to a denser and more compact structure.

4.2. TGA and DTA

TGA and DTA were carried out on selective specimens of PC (the control) and mixes WGP20 and NCWGP20 after 28 days of hydration. Figs. 7–9 present the DTA/TGA profiles of the control mix, WGP20 and NCWGP20, respectively. The DTA/TGA curves show the typical reactions occurring in the cement matrix when subjected to a progressive temperature increase from room temperature up to 1000°C. The DTA/TGA curves of the selective specimens show three main endothermic peaks. The first peak was observed between 60 and 110°C, corresponding to the mass loss on the TGA curve up to 110, which can be attributed to the gradual departure of bound water in some hydrates like CSH and ettringite [27,28,38,39]. The second endothermic peak was detected at about 475°C and represents a new loss in mass starting around 410°C, that corresponds to the de-hydration of CH; hence, the Portlandite decomposes into free lime (dehydroxylation) at =450–550°C [27,28,40,41]. The third peak was observed at =765–785°C, which occurs due to the decomposition of calcium carbonate and escaping of CO2 from the cement matrix [24,26,27,41].

As Fig. 9 shows, the DTA/TGA profiles of NCWGP20 indicates a strong increase in the first peak, which is related to CSH formation, compared to the control specimen in Fig. 7. Inversely, the second peak, which is related to the decomposition of CH, appears considerably smaller than the same peak of the control specimen. This increase in CSH at the cost of CH can be attributed to the consumption of CH by the pozzolanic reaction. This agrees with the remarkable increase in the compressive strength when WGP and NC particles were used to replace part of the PC. Also, it should be mentioned that the DTA/TGA profiles of WGP20 show an increase in CSH and decrease in the CH peak in comparison to the control
specimen, which confirms the increase in compressive strength of WGP20 compared to control specimen.

Variations between the CH content of the control specimen, WGP20 and NCWGP20 are shown in Fig. 10. As presented in Fig. 10, the CH content decreases by adding 20% WGP as a cement replacement, which indicates consumption of CH in the pozzolanic reaction after 28 days of hydration. The reduction of CH content is much greater when NC particles are loaded in mix NCWGP20, which indicates more pozzolanic reaction in terms of the WGP cement matrix. As can be seen in Fig. 10, a good correlation is found in both the TGA and DTA techniques. From the earlier discussion it can be inferred that, when a small quantity of the NC particles is well dispersed in the WGP cement matrix, the hydrated products of cement deposit on the nanoparticles due to their great surface energy, i.e. they act as nucleation sites. Nucleation of hydration products on NC particles further accelerates the pozzolanic reaction and hydration process [19,36], which is confirmed by the XRD results and SEM micrographs.

4.3. XRD

XRD analyses were conducted to investigate the mineralogical composition of selective specimens of PC (the control), mixes WGP20 and NCWGP20 after 28 days of hydration. For comparison, the peak of CH at 18° (2θ) and the peak of CSH at 28.6° (2θ) have been selected [19,38]. As shown in Fig. 11, a sharp peak in CH is observed in the control mix representing the pure hydration product (CH), which is released from the hydration of cement. Evidently, the intensity of the CH peak is decreased in WGP20 and significantly reduced in mix NCWGP20, which reflects the consumption of CH by pozzolanic reaction. On the other hand, the intensity of the CSH peak significantly increased in mix NCWGP20 compared to the control mix, which agrees with the DTA/TGA results in the previous section. Consequently, the XRD results confirm the improvement in the mechanical properties of mixes WGP20 and NCWGP20 compared to the control mix.

4.4. Scanning electron microscopy (SEM)

SEM was carried out in order to study the influence of WGP and NC particles on the microstructure of the cement matrix. Additions of glass powder and NC particles were found to influence the manner of hydration and resulted in differences in the microstructure of hardened cement systems. Fig. 12 shows the microstructure of selective specimens of the PC control, WGP20 and NCWGP20. Fig. 12(a) presents the typical composition of hydrated mortar in the control mix. The microstructure of the control specimen displayed the existence of CSH surrounded by and connected with many needle-hydrates. When a part of cement was replaced by glass powder, the CSH became relatively dense and fine, as shown in Fig. 12(b). As expected, NCWGP20 (Fig. 12(c)) showed a perfectly dense and compact formation of hydration products. SEM micrographs show that the densest mortar structure was observed for the specimen with a hybrid combination of 20% glass and 2.5% NC particles, followed by the mix with 20% glass powder (WGP20). The improvements in microstructure of NCWGP20 could be attributed to the packing effect of NC particles; due to their great surface area, the NC particles fill the interstitial spaces inside the skeleton of cement mortar, which leads to increases in toughness and strength [18].
4.5. Alkali–silica reaction (ASR)

ASR tests were carried out on selective specimens of the PC control, WGP20, WGP50, NCWGP20 and NCWGP50. The percentage expansions in the selected composites are shown in Fig. 13. Evidently, NCWGP20 had less expansion compared to the control mix, followed by WGP20. It is clear that all specimens had expansions of less than 0.2% and, therefore, according to ASTM C1260, the expansion was within accepted limits. The expansion tests showed that the addition of glass powder assisted in hindering the expansion compared to the control specimen, which confirms the results obtained by Shao et al. [2]. Moreover, the hybrid incorporation of glass powder and NC greatly reduced the possible ASR. The role of NC in reducing ASR expansion is therefore in decreasing the amount of CH, which is confirmed by TGA/DTA and XRD results, and hence preventing formation of a swelling gel [42].

4.6. Activity of ground glass and nano clay with lime

Fig. 14 exhibits the compressive strength of the lime–glass (LWGP) and lime nano clay (LNC) mixtures. It is clear from this figure that both LWGP and LNC mixtures satisfied the minimum strength requirement test at 7 days (4.1 MPa) and attained an increase in strength after an additional 21 days of curing in water. Also, the LNC mixture exhibits high pozzolanic activity compared to LWGP, which could be attributed to the smaller particle size and the higher surface area of NC compared to WGP.
5. Conclusions

Green glass powder (5–50% by cement weight) and NC powder (2.5% by cement weight) were tested for potential employment as cement replacement in cementitious materials. The following conclusions can be drawn:

- Based on flexural and compressive strength, the ASR test and the CH content of the plain, glass powder, and NC/glass powder cement mortars, it was observed that the replacement of cement by 20 wt% glass powder and 2.5 wt% NC particles is feasible in a cementitious system.
- Compared to the control mix without glass, high fracture energy, flexural and compressive properties can be obtained when using up to 50% green glass powder as a cement replacement (less 75 μm) after 28 days of hydration.
- Based on the ASR test results, no damaging effect can be detected at a macroscopic level due to the reaction between glass powder and cement paste with particle size up to 75 μm.
- DTA/TGA techniques can be used to assess the hydration of NCWGP cement mortar after 28 days of hydration.
- The addition of NC particles has great potential to accelerate the pozzolanic reaction. It seems that their nano size allows them to react more readily with the CH, thereby increasing CSH conversion at 28 days of hydration. The hybrid combination of NC and WGP was found to be a very effective way to use ground waste glass as a high-volume cement replacement and to achieve good performance at reasonable cost.

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