A Study of the Mechanical Properties of Waste Nano Ceramic Concrete Incorporating Nano-SiO$_2$ Particles

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Abstract:- Waste material recycling through using in concrete manufacturing not only provides a promising resource to produce a high quality concrete, but also helps to properly encounter the problem of waste disposal. It is a good option for use in concrete because waste ground ceramic has a highly resistant structure and cannot be processed by any recycling system and because it is produced in large quantities. Thus, this study focused on three different phases: in the first phase, the use of waste ceramic power which milled to waste nano ceramic (WNC) as a pozzolan in concrete was investigated. Concrete samples with 2, 4, 6, 8 and 10% of waste nano ceramic (WNC) as a pozzolan in concrete was investigated. Concrete use of waste ground ceramic has a highly resistant structure and cannot be processed by any recycling system and because it is produced in large quantities. Thus, this study focused on three different phases: in the first phase, the use of waste ceramic power which milled to waste nano ceramic (WNC) as a pozzolan in concrete was investigated. Concrete samples with 2, 4, 6, 8 and 10% of waste nano ceramic (WNC) as a pozzolan in concrete was investigated. Concrete samples with 2, 4, 6, 8 and 10% of waste nano ceramic (WNC) substitution were made. In the second phase of the study, 1–4% of nano-SiO$_2$ was used as a partial replacement from cement which chemical prepared. The simultaneous effect of using the optimum percentage 3% of nano-SiO$_2$ incorporating with 6% of waste nano ceramic (WNC) was determined (phase c). In all cases, mechanical tests (compressive, slitting tensile and flexural strength) were performed. The results show that replacing waste nano ceramic (WNC) up to 6% and nano-SiO$_2$ up to 3% does not have a significantly negative effect on the mechanical properties of concrete. Furthermore, using any amount of nano ceramic (WNC) in the concrete increase its mechanical properties. In addition, using nano-SiO$_2$ and pozzolan simultaneously leads to improved compressive strength and a reduced water absorption capacity. Therefore, nano-SiO$_2$ can improve the effects of ground ceramic powder on the properties of concrete.

Keywords: Waste nano ceramic , milling, Nano-SiO$_2$ , mechanical properties, waste nano ceramic concrete incorporating nano-SiO$_2$.

I. INTRODUCTION

Reducing the necessary amount of Portland cement without reducing the performance of concrete is significant for big projects that require a large amount of cement. Furthermore, Portland cement clinker production consumes large amounts of energy and has a notable environmental impact, which involves massive quarrying for raw materials because it 1.7 tons are required to produce 1 ton of clinker and the emission of greenhouse and other gases into the atmosphere. Approximately 850 kg of CO$_2$ is emitted per ton of clinker produced [1,2]. Hence, pozzolan and cementitious materials play an important role in concrete production. In recent years, the disposal of waste materials has presented a complex problem for many agencies worldwide, and industries must find ways to reuse their wastes [3]. The replacement of cement in concrete by wastes represents a tremendous saving of energy and has important environmental benefits. In addition, it will also have a major effect on decreasing concrete costs because the cost of cement represents more than 45% of the cost of concrete. According to some authors, the best way for the construction industry to become more sustainable is by using wastes from other industries as building materials [4]. Ceramic wastes, which are durable, hard and highly resistant to biological, chemical and physical degradation forces, cannot be recycled by any existing process. The use of inorganic industrial residual products in the production of concrete will lead to sustainable concrete design and a greener environment [5]. The amount of waste in the different production stages of the ceramic industry ranges from 3% to 7% of daily production [1]. A number of previous studies have examined the use of waste ceramic in concrete as an aggregate replacement [5–8] or partial cement replacement [8–13], such as pozzolan. Lavat et al. [10] observed a decline in strength at early ages. Ay and -nal confirmed the pozzolanic reactivity of waste ceramic powder [9], and Toledo Filho et al. [11] measured a slight increase in compressive strength for cement replacement by brick powder of up to 10–20%. Torgal and Jalali [8] reported a slight decrease in compressive strength and a decline in water permeability and chloride ion diffusion in concrete with 20% of ground ceramics used as Portland cement replacement. On the other hand, Nanotechnology is one of the most important sciences where many researchers studied its effect. Nanotechnology plays an important role in clean up the environment.[14–19] Ferdinand Brandl and Nicolas Bertrand demonstrated a method for using nanoparticles and ultraviolet (UV) light to quickly isolate and extract a variety of contaminants from soil and water.[16] In recent years,
nanofibers were applied for the remediation of a variety of contaminants including chlorinated compounds, hydrocarbons, organic compounds and heavy metals.[18] Nanowaste materials consumed in concrete production is a valuable issue in clean-up the environment. Priya and Vinutha [20] and Givi et al. [21] studied the effect of nanosilica on the rice husk ash concrete. Rice husk ash concrete provides a clean environment by reducing the burning of rice husk ash problem, which is an environmental catastrophe. Presence of nanomaterials in concrete affects its properties. Because of the abundant usage of concrete in the construction, its quality should be improved. Concrete is a highly heterogeneous material produced by mixing of finely powdered cement, aggregates of various sizes with water through inherent physical, chemical and mechanical properties.[14] Colston et al. [22] investigated the effect of inorganic nanoparticles and zeolites on concrete microstructure. The researchers verified the improvement of inorganic nanoparticles and zeolites on concrete microstructure using microelectronics scanning and X-ray fluorescence analysis. Most of the studies investigated the effect of using nanoparticles in cement and concrete utilizing SiO$_2$ and Fe$_2$O$_3$ [23,24]. Jaishankar and Saravana Raja Mohan [25] studied the mechanical properties of nano-SiO$_2$ and nano-Al$_2$O$_3$ concretes. Four different types of ratios were used (0.5, 1, 1.5 and 2). Jaishankar proved that compressive and flexural strength measured at 28th day of the concrete mixed with nano- SiO$_2$ and nano-Al$_2$O$_3$ were higher than that obtained from a plain concrete mix. The incorporation of nanoparticles significantly resisted the cracking behavior of concrete. The influence of nano-ZrO$_2$ (NZ), nano-Fe$_3$O$_4$ (NF), nano-TiO$_2$ (NT) and nano- Al$_2$O$_3$ (NA) on mechanical properties including the compressive and indirect tensile strength in addition to durability of concrete were investigated by Shekaria and Razzaghi.[26]. El-Yamani et al [27] also studied the effect of replacement of cement with different percentages of (1, 2, 3 and 4%) Nano-SiO$_2$ and with constant percentage of silica fume, which the result showed that nano-SiO$_2$ is used to reduce the corrosion in reinforcement bars. Sololev and Gutiérrez [28] mentioned that, the NS acting as a nanofiller in the voids or empty spaces or between particles of calcium silicate hydrate (C–S–H) gel. NS is scatted in the hydration process acting as a nucleation or crystallization centers, by this way the hydration rate increased. As well, NS assisted in the formation of smaller size CH crystals and homogeneous clusters of C–S–H composition. Moreover, researchers founded that NS improves the structure of the transition zone between aggregates and paste. The present work aimed to investigate the effect of using NS and waste nano ceramic (WNC) on the concrete. The mechanical properties including, compressive, flexural and splitting tensile strength are discussed in this article. A comparison was carried out between the improvement ratios obtained by using NS prepared chemically and that obtained from nanowaste materials (WNC), which prepared by mechanical milling and that was the main objective of the present work.

II. MATERIALS

A. Waste ceramic

The waste ceramic used in this study was obtained from recycled ceramic ground tile supplied by cleopatra ceramic factory in Egypt. Cracked pieces of ground tiles were crushed by tabin crusher. At the laboratory scale, Nanowaste materials used are NFA, NSF and NC. Torefine the particles of fly ash, SF and coal from micro- to nanosize high energy milling technique was used. There are different types of milling machines for example milling machine having a rotating cylindrical container along its axis horizontally, planetary milling machine, SPEX shaker mills.[29] Borner and Eckert [30] investigated the effect of energy input by milling iron powders with the use of a SPEX milling machine and a Pulverisette 5, among other lower energy mills. SPEX shaker mill provides the largest input and, therefore, leads to a fast decrease in grain size to less than 20 nm. The Pulverisette mill provides a smaller energy impact during the collision. After 32 hours of milling, the grain size achieved was 40 nm at 90 rpm, 31nm at 180 rpm and 20nm at 360 rpm. The machine used for milling in this research was Fritsch Pulverisette Analyzer, which milling was fixed to 400 rpm. The milling process performed with 2.5mm diameter ball and jar type were fixed to zirconica oxide, Fadzil et al. [31] prepared the nanometaakolin with the same method but using different diameter for the ball. The waste ceramic preparation process before milling is shown in Fig. 1.

B. Nanosilica.

The nanosilica used in this research was prepared at the Beni Suef central laboratories. The particle sizes (nm) and specific surface area (m$^2$/kg) of nano-SiO$_2$ were 14 and 200, respectively. Table I illustrates the chemical composition of nano-SiO$_2$.

<table>
<thead>
<tr>
<th>content</th>
<th>Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>99.65</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.02</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>0.01</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.012</td>
</tr>
<tr>
<td>MnO</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>LOI</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Cement
OPC was used in all mixes, which produced by Misr Beni Suef company (Beni Suef city, Egypt). CEM I 52.5 N was a cement grade used. Cement was tested according to ASTM C150. The physical and mechanical properties and chemical composition of the cement are shown in Table I.

Table II the Portland cement of physical and mechanical properties

<table>
<thead>
<tr>
<th>No.</th>
<th>Property</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific gravity</td>
<td>3.15</td>
</tr>
<tr>
<td>2</td>
<td>Fineness</td>
<td>3200 cm³/g</td>
</tr>
<tr>
<td>3</td>
<td>Initial setting time</td>
<td>86 minutes</td>
</tr>
<tr>
<td>4</td>
<td>Final setting time</td>
<td>195 minutes</td>
</tr>
<tr>
<td>5</td>
<td>Compressive strength</td>
<td>Kg/cm²</td>
</tr>
<tr>
<td>a)</td>
<td>3 days</td>
<td>205</td>
</tr>
<tr>
<td>b)</td>
<td>7 days</td>
<td>307</td>
</tr>
<tr>
<td>c)</td>
<td>28 days</td>
<td>436</td>
</tr>
<tr>
<td>6</td>
<td>Soundness</td>
<td>1mm</td>
</tr>
<tr>
<td>7</td>
<td>chemical composition %</td>
<td>W/(%)</td>
</tr>
<tr>
<td>a)</td>
<td>SiO₂</td>
<td>21.16</td>
</tr>
<tr>
<td>b)</td>
<td>Al₂O₃</td>
<td>5.50</td>
</tr>
<tr>
<td>c)</td>
<td>Fe₂O₃</td>
<td>3.21</td>
</tr>
<tr>
<td>d)</td>
<td>MgO</td>
<td>0.69</td>
</tr>
<tr>
<td>e)</td>
<td>CaO</td>
<td>63.40</td>
</tr>
<tr>
<td>f)</td>
<td>SO₃</td>
<td>2.40</td>
</tr>
<tr>
<td>g)</td>
<td>K₂O</td>
<td>0.50</td>
</tr>
<tr>
<td>h)</td>
<td>Na₂O</td>
<td>0.10</td>
</tr>
<tr>
<td>i)</td>
<td>F.L</td>
<td>2.70</td>
</tr>
<tr>
<td>j)</td>
<td>LOI</td>
<td>2.30</td>
</tr>
</tbody>
</table>

D. Aggregates
The sand and the coarse aggregate used in the concrete were Crushed dolomite aggregates. The water absorption, specific gravity, density and void ratio(%) of the aggregates were specified following the tests methods described in ASTM. The physical properties of the aggregates are given in Table III.

Table III physical properties of dolomite and sand

<table>
<thead>
<tr>
<th>No.</th>
<th>Property</th>
<th>Dolomite</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific gravity</td>
<td>2.66</td>
<td>2.65</td>
</tr>
<tr>
<td>2</td>
<td>Bulk density</td>
<td>1600</td>
<td>1850</td>
</tr>
<tr>
<td>3</td>
<td>Void ratio(%)</td>
<td>39.84</td>
<td>37.73</td>
</tr>
<tr>
<td>4</td>
<td>Percentage of absorption (%)</td>
<td>1.80</td>
<td>2</td>
</tr>
</tbody>
</table>

E. Water
The water used in the concrete was Tap water.

F. Superplasticizer
In this study, the chemical admixture used as superplasticizer was high range water reducer of modified polycarboxylates. It was manufactured according to ASTM C494 (types F). The chemical admixture main concept controls the total performance, whereas allows cement particles delayed absorption and distributed them. High range water reducer superplasticizers obtained a high-quality concrete mix with high strength. Table 6 shows Properties of the superplasticizer.

Table IV Technical Data Properties of the superplasticizer

<table>
<thead>
<tr>
<th>Form</th>
<th>Aqueous solution of modified polycarboxylates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Appearance</td>
</tr>
</tbody>
</table>

III. MIX PROPORTIONS
The present investigation studied the partial replacement of cement by waste nano ceramic powder (phase A) as well in phase B studied the partial replacement of cement by waste nano-SiO₂. Also, the reduced the cement content by adding several combinations of a ceramic powder and nano-SiO₂ (phase B). The mixture is designed according to ACI-211-89. At the beginning of the mixture design, the binder content (350 kg/m³) and water–cement ratio (0.45) were chosen to be constant.

A. Phase A
Mixes were made with waste nano ceramic replacing 0%, 2%, 4%, 6%, 8% and 10% by weight of the cement as pozzolan and with the same amount of reference. The amounts in the concrete mixture are shown in Table V.

C. phase C
Accordingly, concrete mixtures using different mix proportions and optimum percentages combinations of WNC and nano-SiO₂ were initially performed. Eight high strength concrete mixes were optimized and used in the current study.

Table V Mix composition of the investigated samples

<table>
<thead>
<tr>
<th>MIX NO.</th>
<th>O.P.C %</th>
<th>N.S %</th>
<th>N.C %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C1</td>
<td>99</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>C2</td>
<td>98</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>C3</td>
<td>97</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>C4</td>
<td>96</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>CC2</td>
<td>98</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>CC4</td>
<td>94</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>CC6</td>
<td>96</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>CC8</td>
<td>92</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>CC10</td>
<td>90</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>C3+CC6</td>
<td>91</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

C0: control
C1-4:1-4%nano silica
CC2,4,6,8,10: waste nano ceramic

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IV. MIX DESIGN

The concrete mixtures were mixed in accordance with ASTM C 192 in a 120 l drum mixer. The coarse and fine aggregate were mixed first, followed by the addition of the cement, pozzolan and water containing the required amount of Superplasticizer. One fifth of the Superplasticizer was always retained to be added during the last 1 min of the mixing period. The Superplasticizer admixture was used in various amounts to maintain the workability of the fresh concrete. Nanoparticles are not easy to distribute uniformly due to their high surface energy. In order to solve this problem in the previous studies, before adding any nanosilica to the mixture, nanosilica was stirred separately for 1 to 3 min at high speed using with either water or water and Superplasticizer. Having made sure that the particles have been completely dissolved in water, they were added to the mixture. Therefore, in phase B, particles were stirred in water for 1 min at 120 rpm, and then they were added to the mixture. The test specimens were cast in steel cubic moulds (100 X 100 X 100) and compacted on a vibrating table. After approximately 24 h, the specimens were removed from the moulds. The concrete specimens were cured in lime-saturated water at 21 \( ^\circ \)C in cure tanks until the time of testing. Casting, compaction, and curing were accomplished according to ASTM C 192-81. For each mix, cubic samples were tested to determine the compressive strength for each mixture was obtained from an average of three cubic specimens. A 2000-kN capacity uniaxial compressive testing machine was used to test the specimens.

V. RESULTS AND DISCUSSION

A. Compressive strength in phase A

The average results obtained from the sample compression tests at 7 and 28 days are shown in Fig. 2 and given in Table VI. The results obtained indicate, as expected, differences at early curing ages. The 7th day compressive strength varied between 252 and 284 kg/cm\(^2\), and the 28th day strength varied between 286 and 310 kg/cm\(^2\). The highest improvement was observed at 6% WNC. The compressive strength decreased as the proportion of waste ground ceramic in the concrete produced increased. At early curing ages, pozzolan only acts as filler and does not undergo the pozzolanic reaction. The reduction in the early compressive strength is mainly due to the immature pozzolanic reaction in the concrete and the preventive growth of C–S–H gel affected by components in nano waste ceramic [33-34].

B. Compressive strength in phase B

Different NSF percentage specimens are compared to control specimens. The effect of curing age on the compressive strength of the concrete mixtures at 7 and 28 days is presented in Figure 3. The optimum result of compressive strength was at 28 days and with 3% NS by weight of the cement content (C3). Low compressive strength improvement is observed at higher and lower than 3%. The increase in the compressive strength can be attributed to the reaction between the calcium hydroxide present already in lime solution and the nanoparticles resulting in formation of additional C–S–H gel, which is responsible on the compressive strength increase [35]. Tawfik et al. [36] and Ghafari et al [37] confirmed that the optimum amount of cement replacement by nano-SiO\(_2\) in cement paste to achieve the highest compressive strength was 3wt%, which agreed with the present work.

C. Compressive strength in phase C

The results of compressive strength for all of the concrete mixtures used in phase C are presented in Fig. 4, and is shown in Table VI. In general, the compressive strength of the concrete specimens decreased as increasing amounts of waste nano ceramic was replacement. As more cement was replaced by waste nano ceramic, lower compressive strengths were observed. Furthermore, the addition of nano-SiO\(_2\) is helpful for the improvement of the compressive strength in the concrete specimens. The compressive strength developed in concretes containing nano-SiO\(_2\) particles was higher than that of the control sample in every case higher. As mentioned above, nano-SiO\(_2\) is thought to be more effective in the pozzolanic reaction than waste nano ceramic. The strength of the concretes was found to increase as the nano-SiO\(_2\) content increased from 1% to 3%. However, it should be noted that using a higher content of nano-SiO\(_2\) must be accompanied by adjustments to the water or superplasticizer dosage in the mix to ensure that specimens do not suffer excessive self desiccation and cracking. Otherwise, using this much nano-SiO\(_2\) could actually lower the strength of composites instead of improving it, although this was not observed in this study.
Fig. 4. Compressive strength of concrete containing optimum different percentage of waste nano ceramic and nano silica at 7 and 28 days of hydration.

Table VI Results of compressive and splitting tensile and flexural strength tests

<table>
<thead>
<tr>
<th>Mix No</th>
<th>Compressive strength Kg/cm²</th>
<th>Splitting tensile strength Kg/cm²</th>
<th>Flexural strength Kg/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 days</td>
<td>28 days</td>
<td>28 days</td>
</tr>
<tr>
<td>C0</td>
<td>252</td>
<td>276</td>
<td>22</td>
</tr>
<tr>
<td>C1</td>
<td>262</td>
<td>290</td>
<td>24</td>
</tr>
<tr>
<td>C2</td>
<td>286</td>
<td>301</td>
<td>25</td>
</tr>
<tr>
<td>C3</td>
<td>302</td>
<td>337</td>
<td>26</td>
</tr>
<tr>
<td>C4</td>
<td>292</td>
<td>328</td>
<td>24</td>
</tr>
<tr>
<td>CC2</td>
<td>255</td>
<td>288</td>
<td>23</td>
</tr>
<tr>
<td>CC4</td>
<td>269</td>
<td>293</td>
<td>24</td>
</tr>
<tr>
<td>CC6</td>
<td>271</td>
<td>297</td>
<td>25</td>
</tr>
<tr>
<td>CC8</td>
<td>265</td>
<td>292</td>
<td>24</td>
</tr>
<tr>
<td>CC10</td>
<td>258</td>
<td>287</td>
<td>23</td>
</tr>
<tr>
<td>incorporating (3%NS+ 6% NC)</td>
<td>284</td>
<td>317</td>
<td>25</td>
</tr>
</tbody>
</table>

D.SEM Test
To verify the mechanism predicted by the compressive strength test, scanning electron microscope (SEM) examinations are performed. Some samples from all experimental specimens are exposed for the electrographic at a specific period (28 days). This can be shown from Figures (5-b) Nano-SiO² samples have more consolidated and occupy structure compared with the control sample.

Fig 5. (a) SEM of control sample of concrete
Fig 5 (b) SEM of sample containing 3% Nano-SiO²
(c) SEM of sample containing 6% waste nano ceramic

VI. CONCLUSIONS
The possibility of using waste ground ceramic powder and the combination of ground ceramic powder with nano-SiO² as a replacement for cement has been investigated in this study. The waste nano ceramic was used in quantities of up to 10% and nano-SiO² was 1-4% of the cement. The following conclusions can be drawn from the study:

1. The compressive strengths of samples decrease with increasing WNC content, especially at early stages. However, the results show that concrete with WNC ultimately demonstrates only minor strength loss, and WNC exhibits very good pozzolanic reactivity and can be used as a cement replacement. For less than 8% use of the pozzolan, the average decrease in resistance after 7 and 28 days of curing is 2.64% and 1.74%, respectively. This results show that less than 8% replacement of pozzolan has no considerable effect on resistance.

2. Nano-SiO² improves the mechanical properties of pozzolanic samples. The greatest impact of adding nano-
SiO$_2$ on compressive strength was observed at early curing ages. Because the reduction of the compressive strength of concrete due to the use of pozzolana was determined at an early stage, the addition of nano-SiO$_2$ could effectively compensate for it. In addition, using nano-SiO$_2$ resulted in increased slitting and flexural strength in all samples. The use of both WNC and nano-SiO$_2$ resulted in a dramatic increase in the mechanical properties of concrete.

3. A very slight difference in the mechanical properties of concrete with the use of 3% or 4% of nano-SiO$_2$ was observed. Increasing the amount of pozzolan improved the mechanical properties of concrete more in samples with 3% nano-SiO$_2$ compared to those with 4% nano-SiO$_2$, so it can be concluded that the optimum percentage of nano-SiO$_2$ is between 3%.

4. Using this construction industry waste product in the production of concrete converts it into an environmentally friendly material because it reduces the agglomeration of residues and exploits its incorporated energy.

REFERENCES