Review of Mechanical, Durability, and Thermal properties of Light weight concrete containing cenosphere

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Abstract. Compared to conventional concrete, lightweight concrete offers a reduced unit weight, making it easier to handle and transport. Its popularity has surged globally in numerous countries and has proven beneficial for construction purposes. Lightweight concrete often exhibits better thermal insulation properties compared to traditional concrete, contributing to energy efficiency in buildings. Recently, the inclusion of cenospheres in lightweight aggregates is being heavily researched around the world. Ceneosphere addition increases the volume of the concrete mixture because of their smaller size and hollow nature of the particle. This research paper showcases the various applications and advantages of lightweight concrete (LWC) containing cenosphere, along with highlighting the role of different supplementary cementitious materials characteristics and manufacturing methods. Furthermore, the current study examines previous researches on sustainable lightweight concretes and showcases the improvements and advancements in mechanical, durability, and thermal properties obtained when cenospheres were added.

Keywords: Light weight concrete, Mechanical properties, Durability properties, Thermal properties, Supplementary cementitious material

1 Introduction

The production of concrete relies heavily on natural resources, positioning it as the second most utilized material globally following water. This extensive usage has adverse environmental consequences, particularly due to the heightened demand spurred by the expanding construction sector[1], [2]. The increased consumption and production of concrete and its key component, cement, contribute significantly to environmental harm, including escalated greenhouse gas emissions. The cement industry, like many others, grapples with challenges related to carbon dioxide emissions, energy sourcing, material utilization, and resource management. Carbon dioxide is emitted at various stages of cement manufacturing, encompassing fuel consumption, transportation, and production processes. Consequently, there has been a push for the introduction of alternative raw materials in concrete manufacturing to mitigate the overall environmental impact of the construction industry and foster sustainability. This review focuses on investigating the substitution of cementitious materials with lightweight alternatives to produce lightweight concrete, aiming to address these environmental concerns[3], [4], [5]

Research in the field of lightweight and durable concrete materials encompasses the utilization of various additives and aggregates to optimize performance and sustainability in construction applications. Lightweight concrete is a flexible and easily transportable construction material. Its affordability, particularly for larger construction projects, stems from the reduced need for steel reinforcement or additional concrete. The reduced density of lightweight concrete offers several advantages, including improved thermal insulation properties, reduced dead load on structures, and enhanced workability during construction[6], [7], [8]. There are a number of byproducts created during the burning of coal in power plants, including fly ash, cenosphere and bottom ash. The usage of cenospheres in LWC are recently being researched. Also, the coal plant also provides aggregates such as bottom ash which are
less dense and have good thermal properties. Bottom ash aggregate can have qualities like strong compressive strength and good durability that make it useful for a range of applications. Nakararoj et al. [9] investigated that when compared to conventional concrete, the strength of RA concrete decreased by 2.0%, 1.3%, 8%, and 9.8% at 3, 7, 28, and 90 days, respectively. A similar finding was made with concrete that included Ground-Fine Bottom Ash both with and without Coal Bottom Ash, showing that the addition of RCA resulted in a decrease in compressive strength. Lightweight, inert, hollow spheres mostly made of silica and alumina are the characteristics of cenospheres. They are a byproduct of thermal power plants' combustion of coal. Because of these tiny hollow spheres' special qualities such as their high strength-to-weight ratio, poor heat conductivity, and resistance to acids and alkalis, they have a wide range of industrial uses. Celik et al. [10] reported that the Ultra Light Cement Concrete 28-day cube compressive strength fell between 40 and 70 MPa, whereas its equivalent wet density was between 1200 and 1470 kg/m3. With a density of 2400 kg/m3 and a compressive strength of 80-115 MPa, the ULCC's structural efficiency is comparable to that of regular weight concrete. Chanda et al. [11] studied that in the magnesium sulphate attack, hydrated cement undergoes a number of chemical reactions, including those with calcium hydroxide, calcium silicate, and calcium aluminate. The sulphate resistance of concrete mixes with FAC at varying percentages is provided, together with the mass and strength losses resulting from immersion in a magnesium sulphate solution for 28 days. The findings of the 28-day sulphate immersion show that, in comparison to the water-cured samples, the mass of concrete mixes C0, C40, C60, C80, and C100 is somewhat reduced by 0.183%, 0.217%, 0.262%, 0.2815%, and 0.320%, respectively. Lower setting time of cenosphere inherent limitation that can be resolved by adding finer more reactive cementitious substitutes such as silica fume(SF), Alccofine and Metakaolinite(MK). The inclusion of such third SCM can also decrease porosity, boost compressive strength, and improve resistance to chemical attack and shrinkage when added to concrete mixes. Cheng et al. [12] illustrated how MK and slag affect concrete's compressive strength. After 28 days, the concretes' compressive strengths ranged from 37.9 to 48.6 MPa. The findings demonstrate that MK outperformed slag in this investigation when it came to increasing the strength of concrete. MK10 performed best for concretes that exclusively replaced MK or slag, leading to the greatest strength increase over the control specimen at 7 and 28 days.

In this review, the role of cenosphere, different supplementary cementitious materials, aggregate type and manufacturing methods are discussed. Also, the impact of such cenosphere addition and aggregate replacements on the mechanical, durability and thermal properties of LWC is evaluated. By reusing waste materials and reducing the carbon footprint associated with cement manufacturing, the use of industrial by-products and waste materials in building can assist to promote sustainability[13].

2 Methodology

For the present study, large number of literatures were collected related to light weight concrete containing cenospheres and different SCMs. The literatures were assessed based on mechanical, durability and thermal properties of lightweight concrete. The datasets for the review of mechanical properties included were cementitious materials, type of aggregate used and 28-day compressive strength. The datasets used for the review of durability properties included cementitious materials, aggregate type, water absorption, sulphate attack and acid attack. The datasets used for the assessment of thermal properties included cementitious materials, aggregate type, thermal conductivity and temperature difference in the concrete used. Based on the critical analysis the discussions and conclusions were presented. The literature details along with the study incorporated is presented in table 1.

Table 1. Details of the properties studied in the literature

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Authors</th>
<th>Cementitious Materials</th>
<th>Aggregate</th>
<th>Mechanical Properties</th>
<th>Durability Properties</th>
<th>Thermal Properties</th>
<th>Micro-structural Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>[10]</td>
<td>Rheinheimer</td>
<td>OPC, SF, CS</td>
<td>N.A</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>[14]</td>
<td>Al-Sibahi and Edwards</td>
<td>OPC, MK</td>
<td>Sand, Recycled glass</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th></th>
<th>Study</th>
<th>Aggregates</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>Nakararoj</td>
<td>Cement, Ground Fine Bottom Ash (G-FBA)</td>
<td>FA,CA, Coarse Bottom Ash, Recycled Coarse Aggregate</td>
</tr>
<tr>
<td>[11]</td>
<td>Chanda</td>
<td>OPC, FAC</td>
<td>N.A</td>
</tr>
<tr>
<td>[15]</td>
<td>Kelestemu and Demirel</td>
<td>Cement, Metakaolin</td>
<td>N.A</td>
</tr>
<tr>
<td>[16]</td>
<td>Balgourinejja</td>
<td>Cement, Metakaolin</td>
<td>Gravel, Leca, Sand, Limestone powder</td>
</tr>
<tr>
<td>[17]</td>
<td>Danish</td>
<td>Cement, CS</td>
<td>N.A</td>
</tr>
<tr>
<td>[18]</td>
<td>Lu a.</td>
<td>Cement</td>
<td>BA, CA</td>
</tr>
<tr>
<td>[19]</td>
<td>H.K e.</td>
<td>Cement and MK</td>
<td>N.A</td>
</tr>
<tr>
<td>[20]</td>
<td>Najeeb and Mosaberpanah</td>
<td>Cement, CS and Nano-Silica</td>
<td>FA: Sand</td>
</tr>
<tr>
<td>[21]</td>
<td>Strzalkowski</td>
<td>Cement and CS</td>
<td>FA: Sand</td>
</tr>
<tr>
<td>[22]</td>
<td>Haddadian</td>
<td>Cement</td>
<td>FA: Coal Bottom Ash and Sand</td>
</tr>
<tr>
<td>[23]</td>
<td>Beddu</td>
<td>OPC</td>
<td>CA</td>
</tr>
<tr>
<td>[25]</td>
<td>Yang</td>
<td>Cement, Undensified SF, Quartz powder and CS</td>
<td>NA</td>
</tr>
<tr>
<td>[26]</td>
<td>Taewan Kim</td>
<td>Slag Cement, CS</td>
<td>FA and CA</td>
</tr>
<tr>
<td>[27]</td>
<td>Liu et al</td>
<td>Cement, CS</td>
<td>FA and CA</td>
</tr>
</tbody>
</table>

Note: NA - Normal Aggregate, FA - Fine Aggregate, CA - Coarse Aggregate, BA - Bottom Ash

### 3 Discussions
Compressive strength is the most important mechanical property of lightweight concrete. The compressive strength variation with respect to different SCM addition are presented in table 2. Compressive strength appears to be increased by 9% compared to regular concrete when Rheinheumer et al.[10] added alternatives such silica fume and cenosphere. Sibahy et al.[14]
reported that the utilization of Metakaolin as a cementitious material in combination with various aggregates yielded a strength of 19.6 Mpa. In the absence of SCM, the strength obtained was 18.9 Mpa. Strength decreased by 5.6% as compared to conventional concrete by Nakararoj et al.[9] using ground fine bottom ash as a substitute. Finally, Klestemur et al.[15] found that an 8.64% increase in strength was obtained by substituting MK for cement and used regular aggregates Balgourinejad et al.[16] study found that the compressive strength increased by 4.86% when MK was used in place of cement and different aggregates were employed. Utilizing MK as a replacement, Kim et al.[19] discovered an 18.42% gain in strength. Cheng et al.[12] study found that adding MK and slag increased strength by 17.39% compared to conventional concrete. Najeeb et al.[20] discovered that employing CS and Nano Silica as alternatives enhanced the strength to 60 MPa. Using only NS boosted the strength to 72 Mpa, whereas using only CS produced a strength of 56 Mpa. When no substitutes were utilized, the strength was 64 Mpa. Strzalkowski et al.[21] reported a 49.09% gain in strength with CS substitutes. Haddadian et al.[22] produced a 55.5% increase in strength by employing Coal Bottom Ash as aggregate. Beddu et al.[23] investigation discovered that utilizing cenosphere instead of ordinary cement boosted the concrete's strength by 59.6% to 28.8 Mpa. Majhi et al.[24] research revealed that employing silica fume as a cement substitute resulted in a strength of 30 Mpa, but without the substitution, the strength reduced by 6.25% to 32 Mpa. Yang et al.[25] experiment discovered that utilizing CS as a substitute for cement resulted in a strength of 60 Mpa, but using SF resulted in a strength of 92 Mpa, a 34.78% reduction. According Liu et al.[27] research, utilizing Non-perforated CS as a cement substitute resulted in a strength of 70 Mpa, whereas Perforated CS resulted in 78 Mpa. The normal strength of concrete was 75 Mpa. Using BA and MK as alternatives improved the strength. According to Kumar et al.[28] research, 66 Mpa strength was obtained when BA was used in place of cement. When MK and BA were combined as replacements, the strength rose to 77 Mpa. When MK was used alone, the strength was only 35 Mpa, a 54.54% reduction from the combination of the two substitutes.

3.2 Durability property

The durability improvements noted for the lightweight concrete made with CS are presented in table 3. From the table, it can be seen that the addition of CS as binary or ternary cementitious material has significant effect on on durability properties such as water absorption, sulphate attacks, water attacks. Nakararoj et al.[9] discovered that concrete with recycled aggregates (RA) had the highest shrinkage, while a mixture of 50% G-FBA and 50% CBA had lower shrinkage Chanda et al.[11] found that adding CS improved resistance to sulphate and acid attacks. Kelestemur et al.[15] showed that using metakaolin as a cement replacement improved corrosion resistance. Lu et al.[18] found that incorporating MSWIBA reduced water absorption in concrete. Kim et al.[19] found that the density of concrete with FB1 aggregates increased to around 1790 kg/m3 when they replaced it with metakaolin. And for FB2 aggregates, the density went up from 1651 kg/m3 to 1765 kg/m3 as the replacement of metakaolin increased from 0% to 20%. In Cheng et al.[12] study, they discovered that adding 10 wt% and 20 wt% metakaolin to concrete improved the pore structure and significantly reduced shrinkage strain. And according to Najeet and Mosaberpanah [20] research, adding CS (calcium silicate) to concrete had a slight impact on water absorption. The water absorption rate was 3.8% without CS and increased to 4.2% when 10% CS was added. Strzalkowski et al.[21] found that adding CS(0%) resulted in 2.5% water absorption, while adding CS(20%) increased it to 3.8%. Haddadian et al.[22] used coal bottom ash and found that CBA(0%) had 12.96% water absorption, while CBA(25%) had 20.15%. Majhi et al.[24] found that SF(0%) had 17.1% water absorption, but adding SF(10%) reduced it to 11.3%. Kim[26] found that adding 50% slag and CS resulted in 33.71% water absorption, while adding 50% slag alone increased it to 36.20%.
Fig. 1. (a) Mass loss due to sulphate (b) Mass loss due to acid (c) Depth of chloride penetration [11]  

Table 3. Water absorption of LWC mixtures

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Cement</th>
<th>SCM 1</th>
<th>SCM 2</th>
<th>Aggregate</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[20]</td>
<td>OPC</td>
<td>-</td>
<td>-</td>
<td>NCA,NFA</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>OPC</td>
<td>CS</td>
<td>-</td>
<td>NCA,NFA</td>
<td>4.2</td>
</tr>
<tr>
<td>[21]</td>
<td>OPC</td>
<td>-</td>
<td>-</td>
<td>NCA,NFA</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>OPC</td>
<td>CS</td>
<td>-</td>
<td>NCA,NFA</td>
<td>3.8</td>
</tr>
<tr>
<td>[22]</td>
<td>OPC</td>
<td>-</td>
<td>-</td>
<td>NCA,NFA</td>
<td>12.96</td>
</tr>
<tr>
<td></td>
<td>OPC</td>
<td>CBA</td>
<td>-</td>
<td>NCA,NFA</td>
<td>20.15</td>
</tr>
<tr>
<td>[24]</td>
<td>OPC</td>
<td>FAC</td>
<td>-</td>
<td>FA,CA,SFA</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>OPC</td>
<td>FAC</td>
<td>SF</td>
<td>FA,CA,SFA</td>
<td>11.3</td>
</tr>
<tr>
<td>[26]</td>
<td>OPC</td>
<td>Slag</td>
<td>-</td>
<td>FA,CA</td>
<td>36.20</td>
</tr>
<tr>
<td></td>
<td>OPC</td>
<td>Slag</td>
<td>CS</td>
<td>FA,CA</td>
<td>33.71</td>
</tr>
</tbody>
</table>

Note: SFA - Sindered Fly Ash

3.3 Thermal property

In the present study, thermal conductivity (W/Mk) was used to assess the thermal performance of lightweight concrete containing CS. A significant improvement in thermal performance was observed for CS as ternary mixture. Fig.1 shows the reduction in thermal conductivity observed in past studies. Rheinheimer et al. [10] conducted experiments where they added SF and CS to the concrete mixture. In their first trial, they achieved a thermal conductivity of 0.40 W/mK. However, in the second trial, after adding SF, they were able to achieve a lower thermal conductivity of 0.84 W/mK. This reduction in thermal conductivity amounted to a 52% decrease. Sibahy et al. [14] also explored the thermal conductivity of modified concrete mixes compared to a reference sample. They found that at both ambient...
temperature and at a higher temperature of 600 degrees Celsius, the thermal conductivity of
the modified mixes was lower than that of the reference sample. This suggests that the
changes made to the concrete mixture had a noticeable impact on its ability to conduct heat.
Previous research has also provided us with some interesting insights into the thermal
conductivity values of various components. For instance, cement has a thermal conductivity
of approximately 0.19 W/mK, dry glass measures around 0.35 W/mK, metakaolin registers
at 0.29 W/mK, and dry natural sand has a thermal conductivity of about 0.18 W/mK. These
values give us a better understanding of the individual contributions of these components to
the overall thermal conductivity of concrete. Balgourinejad et al.[16] conducted experiments
where concrete samples were exposed to high temperatures. They observed that as the
temperature increased, the samples turned white and exhibited an increase in the formation
of cracks. Additionally, there was a loss of mass, indicating the effects of high temperature
on the structural integrity of concrete. Strzalkowski et al.[21] explored the impact of
cenosphere concentration on thermal conductivity. In the same study it was found that, as the
concentration of cenospheres increased, the thermal conductivity of the concrete decreased.
This suggests that cenospheres can be used as an effective means to reduce heat transfer in
concrete structures. Beddu et al.[23] conducted experiments with CS, or silica fume, as an
additive. They achieved a thermal conductivity of 1.0795 W/mK with 10% CS, and a slightly
lower thermal conductivity of 0.9463 W/mK when the CS concentration was increased to
20%.

Fig. 2. Thermal conductivity of different mixes from past studies

4 Conclusion

From the present study containing mechanical, durability and thermal performance of
lightweight concrete containing cenospheres, the following conclusions were drawn.
1. The unit weight of light weight concrete reduces to a greater extent with the addition
   of cenosphere, because of the hollow nature and increased surface area of the
cenosphere particle.
2. The compressive strength of LWC containing cenosphere increased in later ages,
   but exhibited poor early strength development. This shortcoming was eliminated
   with the addition of a third cementitious material such as SF and MK.
3. The porous nature of LWC increased the water absorption of concrete. This increase
   in water absorption can be reduced by adding finer particle such as SF and MK. The
   chloride and corrosion resistance of LWC improved with the addition of
cenospheres.
4. Aggregate type used in LWC also plays a vital role in the durability and thermal
   performance of concrete. Recycled and artificial aggregates are less durable but
   provide good thermal insulation properties. Addition of cenospheres in such LWC
   increases the durability performance.
5. This decrease in thermal conductivity was noted up to a greater extent by adding cenospheres as cement substitute for concrete containing only OPC. For SCM blended concrete, the addition of cenospheres as ternary material further reduced the thermal conductivity.

The authors declare that they have no conflict of interest.

References


