Properties of concrete with binary binder system of calcined dolomite powder and rice husk ash

Mostafa Shaaban*

Giza Higher Institute for Engineering and Technology, Egypt

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ABSTRACT

This study investigates the properties of a binary binder system consisting of calcined dolomite powder (CDP) and rice husk ash (RHA). To conduct the study, a reference mixture containing 100% ordinary Portland cement (OPC) and six other concrete mixtures containing a binary binder system with different proportions of CDP and RHA were prepared and tested. Testing was conducted for workability, setting time, dry shrinkage, and mechanical strength at different curing times. The results indicate that the binary system CDP-RHA have mechanical properties better than that of OPC. In addition, the results indicate that the mixture containing 50% CDP and 50% RHA is optimal in terms of mechanical strength.

1. Introduction

Cement is the most widely used construction material worldwide. Nevertheless, the cement industry faces environmental and energy challenges, including the following: 1) Generation of between 5% and 10% of the world's total anthropogenic CO2 emissions [1, 2]; the production of cement releases 0.73 to 0.99 t CO2/t cement depending on the clinker-per-cement ratio, manufacturing process, and fuel type [3, 4]; 2) Waste material from the cement industry reaches up to 20%, including cement kiln dust production from 54 to 200 kg/t of produced cement clinker [5, 6]; 3) Production of one t of cement requires the extraction of about 1.5 t of raw material from the earth's surface [7]; 4) Clinker is made by a dry or wet manufacturing process at a temperature around 1400–1600 °C [8] where the dry process requires 3.35 MJ/kg of clinker and the wet process requires 5.4 MJ/kg of clinker [9]. Consequently, it is necessary to seek environmentally friendly materials as alternatives to cement to reduce the adverse environmental impact, minimise raw material waste, and reduce energy requirements. Limestone powder, marble dust, fly ash, rice husk ash, and silica fume, which have been studied as cement replacements at different levels, all have positive effects on the properties of mortar or concrete [10, 11]. This study emphasises the use of calcined dolomite powder (CDP) and rice husk ash (RHA) as a binary binder system because they generate no waste or bypass dust. The overall CO2 emissions from the dolomite calcination process have been reported to be 73% lower than those of cement [12]. The embodied energy of RHA is -26 MJ/kg, where the negative sign indicates energy produced in the overall process [13]. In the next two subsections, a review of the previous studies available dealing with the use of dolomite powder and rice husk ash as a cement replacement is provided.

1.1. Rice husk ash

Rice husk is one of the most suitable sources of pozzolanic material among agricultural waste, as it is available in large quantities and contains a relatively large amount of silica. RHA, produced from burning raw rice husk, primarily contains silica, carbon, and alkali oxides [14]. For decades, researchers have studied the use of RHA in concrete. In 1973, Mehta investigated the effect of pyro-processing on the pozzolanic reactivity of RHA, as reported by Nehdi et al. [15]. RHA can be used to improve the mechanical and durability properties of traditional concretes [16]. Rodriguez [18] found that it is possible to produce high-strength concrete using RHA as a cement replacement. Kishore et al. [19] concluded that the workability of concrete decreases with an increase in RHA above 10%. They also concluded that the optimum replacement level of RHA is 10% for concrete of grade M40 and M50. Hesami et al. [20] studied the effects of RHA on the properties of pervious fibrous concrete pavement and reported that 12% of RHA is most suitable for concrete pavement. Ganesan et al. [21] reported that the replacement of cement with 35% RHA reduces the water permeability and bleeding of concrete. Aminul and Talukdar [22] studied the effect of a binary system of RHA and silica fume (SF) on the rheological properties of concrete. They found that a combination of RHA and SF
yielded suitable rheological performance for moderating plastic viscosity and low yield stress. According to Mehta and Folliard [23], mortars containing RHA possess excellent acid and sulphate resistance compared to that of zero RHA mortars.

1.2. Dolomite powder

Dolomite is a double carbonate of calcium and magnesium (CaCO3MgCO3) and has a theoretical content of 45.7% MgCO3 and 54.3% CaCO3 [24].

According to Samtani et al. [25], dolomite decomposes to an oxide in one step in an inert atmosphere, as shown in Eq. (1):

\[ \text{CaMg(CO}_3\text{)}_2 \rightarrow \text{CaO-MgO + 2CO}_2 \]  

(1)

In an atmosphere containing CO2, the calcination process occurs in two steps: the decomposition of magnesite at 770 °C, followed by the decomposition of calcite at 915 °C. These reactions are shown in Eqs. (2) and (3) [26]:

\[ \text{MgCO}_3\text{CaCO}_3 \rightarrow \frac{1}{2}\text{MgO-CaCO}_3 + \frac{1}{2}\text{CO}_2 \]  

(2)

\[ \text{MgO-CaCO}_3 + \text{heat} \rightarrow \text{MgO-CaCO}_3 + \text{CO}_2 \]  

(3)

Attempts have been made to investigate the utilisation of natural dolomite as a substitute material for cement. For example, Balakrishnan and Paulose [27] stated that dolomite acts as cement when replaced at a MgO substitution range of 30%

1.3. Research significance and contribution

As mentioned in Section 1, the use of OPC causes environmental pollution and requires high consumption of natural raw materials and energy. This study was performed to find an alternative cement binder to reduce CO2 emissions and minimise the consumption of natural raw materials and energy. The suggested alternative binder consists of a mixture of CDP and RHA. This study also evaluates the impact of various levels of CDP and RHA in terms of fresh and hardened properties to determine the optimal levels of CDP and RHA.

2. Experimental programme

2.1. Materials

Natural crushed dolomite with a specific gravity of 2.65 and a particle size range of 4.75–12.5 mm was used as a coarse aggregate in all mixtures, while a fine aggregate of natural sand with a specific gravity of 2.5 was used in all concrete mixtures. The properties of the used aggregate meet the specifications of ASTM C33/C33M-18 [35]. OPC CEMI-42.5N complying with ASTM C150/C150M-19a [36] was used in the control mixture, while CDP obtained from dolomitic rock, treated by a calcination process according to the literature [26], was used with RHA as a cement alternative in the other six concrete mixtures. The CDP used has a particle size range of 0.5–110 μm and a specific gravity of 2.76, and the RHA was finer than 50 μm and complies with ASTM C618-12 [37]. The chemical constituents of OPC, CDP, and RHA are listed in Table 1. Potable water complying with ASTM C1602/C1602M-18 [38] was used for mixing and curing. Sikament-163M, which meets the requirements of ASTM C494/C494M-15 Type F [39], was used at a dosage of 1% in all mixtures as a superplasticizer.

2.2. Mix proportion

Seven concrete mixtures were prepared according to the detailed proportions given in Table 2. All mixtures have the same water/binder ratio of 0.42 and a superplasticizer dosage equal to 1% of the binder weight. The control mixture contains 100% OPC, while the other six mixtures contain zero OPC, as shown in Table 2. The concrete mixtures containing different percentages of CDP and RHA are denoted as C100, D80R20, D70R30, D60R40, D50R50, and D80R20, where C100 is 100% OPC and the numbers following D and R indicate the percentages of CDP and RHA, respectively.

2.3. Specimens preparation and testing methods

Mixing was performed in a laboratory mixer for a suitable time to obtain a homogeneous mix, and then samples were taken to perform the required tests on the fresh concrete. To prepare the specimens needed for hardened concrete tests, fresh concrete was poured into steel moulds of the required shapes and sizes for each test. After 24 h, the moulds were removed and the specimens were cured in a water basin until the day of testing. The workability of fresh concrete was measured using a slump cone (200 Φ mm, 100 Φ mm, and 300 mm height) according to ASTM C143/C143M-05 [40]. To measure the setting time of the developed concrete mixtures, six specimens were tested to determine the initial and final setting times in accordance with ASTM C403/C403M-16 [41]. To measure the drying shrinkage of each concrete mixture, 12 concrete prisms of 25 × 25 × 285 mm were prepared and cured in a room at 22 ± 1 °C and a relative humidity of 95 ± 2%. The changes in length of the standard samples were measured according to ASTM C490/C490M-17 [42] after ageing for 7, 28, 56, and 90 d after the specimens were exposed to the drying environment. To evaluate the compressive strength of each mixture, 12 cylindrical specimens of 300 × 150 Φ mm were tested at 7, 28, 56, and 90 d according to ASTM C39/C39M-18 [43]. The splitting tensile strength was tested using 12 cylindrical specimens of 300 × 150 Φ mm as per ASTM C496/C496M-17 [44] after ageing for 7, 28, 56, and 90 d. The flexural strength was determined by carrying out the test procedure according to the ASTM C293/C293-18 [45] standard using 12 concrete beams of 100 × 100 × 500 mm at 7, 28, 56, and 90 d.

3. Results and discussion

3.1. Workability

Figure 1 presents the results of slump tests conducted for the seven concrete mixtures. The results indicate that the slump of the reference...
The mixture was higher than the slump of the other mixtures. In addition, the slump value obtained decreased with a decrease in CDP percentage and an increase in RHA percentage. The concrete mixtures D80R20, D70R30, D60R40, D50R50, D40R60, and D30R70 have slump values lower than that of the reference mixture by 4.4, 15, 22.4, 33, 42.3, and 48.5%, respectively. This behaviour is attributed to the porosity of RHA, whose particles contain macro-and meso-pores inside and on the surface, resulting in a very large specific surface area. Subsequently, a greater amount of water is required to wet this large surface area, resulting in a decrease in free water, a lower slump, and the water/binder ratio. The superplasticizer dose was maintained constant in all mixtures. The same conclusion was stated by Van et al. [46] and Habeeb et al. [47]. In addition, Kishore et al. [19] reported that the workability of concrete decreases with an increase in RHA content above 10%.

3.2. Setting time

Setting time results are presented in Figure 2. These results show that the setting time of the reference mixture containing 100% OPC is less than those for the CDP-RHA mixtures. For instance, the initial setting times for the mixtures made with 80, 70, 60, 50, 40, and 30% CDP increased dramatically by 21, 40, 44, 52, 58, and 67%, respectively, and the final setting times of these mixtures were higher by 10.6, 13.9, 17.6, 26, 32, and 37%, respectively. It is observed that a lower content of CDP and higher content of RHA lead to a lower rate of hardening. Reducing the amount of CaO&MgO by increasing RHA level in the mixture causes a decrease in the amount of CaO, which is needed to accelerate the setting and for rapid formation of calcium-silicate-hydrate gel (C-S-H) [48]. The slower setting of mixtures containing RHA may be due to the low rate of hydration in these mixtures [49].

3.3. Drying shrinkage

The drying shrinkage strain of the investigated mixtures is presented in Figure 3. The reference mixture containing 100% OPC has a higher shrinkage value than that of the other mixtures, and the shrinkage of all mixtures increases with curing time. After 90 d, it was 79% higher than its value at 7 d. In general, the recorded results show that the shrinkage of the mixtures containing CDP and RHA was less than that of the reference mixture and increased slightly with a decrease in the CDP level. For example, mixtures with 80, 70, 60, 50, 40, and 30% CDP had drying shrinkage values that were 43, 54.2, 56, and 58.6% less than that of the reference mixture at 7 d, respectively, and 29.8, 40.9, 41, and 39.6% less than that of the reference at 90 d, respectively. The reason for this behaviour is that the volume of Mg(OH)2 produced from the hydration of MgO (included in CaO&MgO) is greater than that of its initial reagents [50]; consequently, this expansion reduces the shrinkage due to the hydration of CaO.

3.4. Compressive strength

The results of compressive strength tests are shown in Figure 4. They indicate that the strength of all concrete mixtures increases over time. The lowest compressive strength among all the mixtures was observed for the D30R70 concrete mixture, and the value was less than that of the reference mixture (which had the second lowest compressive strength) by 4, 13, 8, and 1% after 7, 28, 56, and 90 d, respectively. The highest compressive strength was exhibited by the D50R50 concrete mixture, at 73.4 MPa after 90 d, followed by D60R40 at 72.8 MPa. The strength of D50R50 was higher than that of the reference mixture by 70, 68.5, 70.7,
and 93.2% after 7, 28, 56, and 90 d, respectively. Figure 4 also shows that the concrete mixtures D80R20, D70R30, D60R40, D50R50, and D40R60 have 7-d compressive strength values that are 56.9, 73.1, 73, and 15.4% higher than that of the reference mixture, respectively, while their 90-day compressive strength is 62.4, 91.6, 93.2, and 14.5% higher than that of the reference mixture, respectively. This indicates that the combination of CDP (i.e., CaOMgO) and RHA provides a significant increase in compressive strength compared with the reference mixture. This result can be explained as follows: when CaOMgO is hydrated in the presence of reactive silica in RHA, CaO reacts with water to produce C-S-H and calcium hydroxide (CH), while MgO hydrates to magnesium silicate hydrate gel (M-S-H), which is analogous to C-S-H [51], and magnesium hydroxide Mg (OH)2. With further curing, both CH and Mg (OH)2 react with reactive SiO2 in RHA and generate greater amounts of C-S-H and M-S-H, resulting in higher strength with ageing, which is in agreement with previous studies [52, 53]. A previous study also stated that activated light-burned dolomite shows higher mechanical properties and durability performance in cement composites [54].

3.5. Splitting tensile and flexural strength

The splitting strength results of the tested mixtures are shown in Figure 5. These results follow the same pattern as the compressive strength results; therefore, it can be said that an increase or decrease in tensile strength is due to the same reasons that lead to an increase or decrease in compressive strength. This implies that as the compressive strength increases, the tensile strength also increases. The experimental observations indicate that the tensile strength of the D50R50 mixture is higher than that of the control mixture (100% OPC) by 38.5, 32.4, 39.5, and 45.8% after 7, 28, 56, and 90 d, respectively. The optimum mixes are D60R40 and D50R50, whose compressive strengths are higher than those of the reference mixture by 38.5, 32.4, 39.5, and 45.8% after 7, 28, 56, and 90 d, respectively. A decrease in flexural strength may be due to an excess quantity of unreacted RHA after dehydration of CaOMgO is depleted, which causes an increase in the defect density. According to Duxson et al. [55], increasing the defect density increases the potential methods of flexural failure.

4. Conclusions

In this study, seven concrete mixtures were prepared and tested after curing for various times to investigate their fresh and hardened properties. From the results, the following conclusions can be drawn:

1. In general, the developed binary binder system consisting of CDP and RHA gives promising results compared with the results of ordinary Portland cement in terms of workability, drying shrinkage, and mechanical strength.
2. The binary binder system consisting of 50% CDP and 50% RHA provides better properties than ordinary Portland cement.
3. At fixed water-to-binder ratio and superplasticizer dosage for all mixtures, the concrete mixtures with CDP-RHA mixtures have a slump less than that of the reference mixture by percentages ranging from 4.4% to 48.5%.
4. The dry shrinkage of concrete mixtures containing CDP-RHA is less than that of the reference mixture, by percentages ranging from 30% to 59%.
5. The setting times of the CDP-RHA binary binder are higher than those of the reference mixture, by percentages ranging from 20.5 to 66.8% and 10.6–37.1% for the initial and final setting times, respectively.
6. In terms of mechanical properties, all concrete mixtures with CDP-RHA (except D30R70) exhibit higher strength than those of the reference mixture, and the optimum mixes are D60R40 and D50R50, whose compressive strengths are higher than those of the reference mixtures by 73.1% and 70% after 7 d and 91.6 and 93.2% after 90 d, respectively.

5. Future work

To confirm the present findings, further studies are required to investigate the characteristics related to the durability and long-term performance of the binder, as these were not addressed in this study.
M. Shaaban

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Declarations

Author contribution statement

Mostafa Shaaban: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data will be made available on request.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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