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Recycled Dredged Sediments as a Supplementary Cementitious Materials in Concrete Production

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Calcined clay is increasingly used in construction applications due to its pozzolanic effect. This research paper investigates the potential use of calcined recycled dredged sediments as an eco-friendly supplementary cementitious material in partial replacement of ordinary portland cement (OPC). The main objective of this research is to reduce cement consumption in concrete production process to minimize the carbon footprint of produced concrete and increase the overall project sustainability. Five concrete mixes were designed including one control mix (with zero calcined clay sediment replacement) and four mixes with stepwise replacement of OPC using calcined clay sediment at ratios ranging from 10% to 40% (by weight). Produced mixes are prepared using consistent batching, mixing, pouring, compaction, and curing procedures to quantify the impact of calcined clay variation on concrete properties. The compressive strength test results of concrete mixes showed that calcined clay can successfully replace OPC up to 30% (by weight) without reducing concrete compressive strength. The successful incorporation of calcined clay sediment in concrete industry will significantly reduce the negative impact of concrete construction projects on the surrounding environment and participate in the increased LEED rating of concrete buildings.

Key Words: Calcined Clay, Compressive Strength, Hydration, Cement, SCM; Supplementary Cementitious Material, LEED

Introduction

The construction industry represents almost 10% of the United States gross domestic product. Concrete is the number one construction material used to pour plain, reinforced, and prestressed components of the construction project (Akhnoukh and Ekhande, 2021). Ordinary portland cement (OPC), used in concrete mixes, is produced using a high-energy consuming process and results in significant carbon dioxide emissions. In recent two decades, several research projects have targeted OPC reduction by developing high strength concrete mixes to minimize concrete cross section (Akhnoukh and Buckhalter, 2021, Akhnoukh, 2008) or through the partial replacement of OPC using supplementary cementitious materials including silica fume (micro-silica), fly ash, rice hulls, blast furnace slag, and calcined clay, also known as metakaolin.

The main objective of this research is to investigate the possibility of using calcined dredged clay sediment as a supplementary cementitious material (SCM) in partial replacement of OPC in concrete production. Calcined dredged clay sediment is used in stepwise replacement of OPC (by weight) to produce multiple concrete mixes with different replacement percentages. The compressive strength of developed mixes is measured and compared with control specimens produced using OPC only to quantify the pozzolanic capabilities of calcined clay and its contribution to concrete strength development.

Literature Review

The use of SCM in concrete mix design has gained significant traction in recent decades due to increased demand to produce environmental-friendly concrete mixes and minimize the carbon footprint of construction projects. This traction is enhanced by the increased attempts of attaining LEED certification for different types of construction projects. Various micro- and nano sized SCMs are used in improving concrete mixes (Akhnoukh, 2020a, 2013). In a relevant research project, silica fume and fly ash were used to produce ternary high strength concrete mixes for precast/prestressed bridge industry (Akhnoukh and Elia, 2019, Akhnoukh and Soares, 2018). In addition to final strength, early setting and high early strength of SCM-infused concrete mixes allows for expedited construction and repairs (Akhnoukh, 2020b). Similarly, nano- and micro-sized particles were incorporated in concrete mixes to reduce air pollution (Elia et al., 2018). SCMs as fly ash, blast furnace slag, and silica fume are successfully used in increasing concrete durability by mitigating the deleterious alkali-silica reactivity (Akhnoukh and Mallu, 2022, Akhnoukh et al., 2016, Deschenes and Hale, 2017a, b, and Folliard et al., 2007). More recently, SCMs were incorporated in concrete mixes used in additive manufacturing applications (Akhnoukh, 2021, Akhnoukh et al., 2021, and Edmunson et al., 2018)

In recent years, calcined clay has been investigated for its potential use in OPC partial replacement (Sharma et al., 2021, Jaskulski et al., 2020, Scrivener at al., 2018, Sabir et al., 2001). Calcined clay usage is attributed to its abundance in natural deposits. Calcined clay, or metakaolin, is produced by thermal treatment (calcination) of kaolin clay under specific temperature for a predetermined duration to produce metakaolin. Calcination temperature and duration depends on the quality of clay, particle size, and kaolin percentage. Several research projects suggest optimum temperature ranging from 600^o to 700 ^{o}C (1112 to 1292 F) for a heating time ranging from 60 to 90 minutes (Khaled et al., 2023 and Ilic et al., 2010). This calcination process results in deriving water off mineral kaolinite ($AL_2O_3.2SiO_2.2H_2O$) and collapse the material structure resulting in aluminosilicate ($Al_2O_3.2SiO_2$) metakaolin. This chemical process is known as dihydroxylation (Murat and Driouche, 1988) and responsible for the calcined clay pozzolanic activity. The pozzolanic activity is defined as the ability of the calcined clay to react with calcium hydroxide in the presence of water to form a cementing product. Pozzolanic activities are determined by direct methods (Cabrera and Rojas, 2001 and Badogiannis et al., 2005) based on measuring the amount of lime reacted or indirect method through the evaluation of hardened concrete strength (Wild and Khatib, 1997).

The effectiveness of calcined clay as a SCM and its ability to enhance the concrete mechanical properties including workability, compressive strength, and modulus of elasticity is dependent on raw clay fineness and calcination temperature (Ferreiro et al., 2019). Research have shown that the use of calcined clay in partial replacement of 20 to 25% of OPC weight results in increased compressive strength. Calcined clay replacement up to 40% of cement weight results in higher strength values beyond 28 days (Thienel and Beunter, 2012). Similar research reported that the optimum rate of using calcined clay in concrete mix designs is 10%. The optimized percentage of replacement is attributed

to the well-compacted structure of hardened concrete reported by SEM micrograph (Olofinnade and Ogara, 2021).
In this research, dredged clay sediments from the York river in Gloucester, Virginia are treated and dehydroxylated for pozzolanic activity enhancement. The developed calcined clay is used in concrete mix development in partial replacement of OPC. Hardened concrete compressive strength is tested at ages ranging from 24 hours to 28-days to quantify the effectiveness of calcined clay. Calcination process, concrete mix design, and detailed experimental investigation are shown in the following sections.

Materials and Methods

In this research, calcined clay will be used in partial replacement of Type IL cement in producing concrete mixes with low carbon footprint. Calcined clay is prepared by dihydroxylation of dredged sediments disposed in upland or ocean disposal sites. A representative dredged clay-rich sediment from the York River, VA is used for the calcination process (see figure 1).

Figure 1. Dredged clay-rich sediment used for calcination

Calcined Clay Production

Dredged clayey material was calcined using and indirect rotary calciner. The raw clay had a bulk density of 60.2 lb./ft^3, the calciner maintained an average temperature ranging from 750 ºC to 800 ºC (1292 to 1472 F). The calciner feeding rate had an average of 20 lb./hr. and clay average calcination duration was 45 minutes. Clay samples were cooled using a counter-current flow of air resulting in pink-color activated calcined clay (see figure 2).

Figure 2. Calcined clay final product

Produced calcined clay is milled to increase the particle surface area and enhance its pozzolanic activity. Milled particles had a specific surface area of 2106 m^2/kg., and a maximum particle size of 85.8 μm.

Experimental Investigation

The pozzolanic activity of calcined clay was indirectly evaluated using compressive strength test result. A two-phase experimental investigation was conducted for pozzolanic activity investigation, as follows:

- Phase I: five different concrete mixes are developed using type IL portland cement, calcined clay, fine sand, and water. A control mix with 30% cement: 70% sand (by weight) and a water-to-cement ratio (W/C) of 0.45, and four mixes using calcined clay in step wise replacement of cement. Calcined clay replaced 10%, 20%, 30%, and 40% of portland cement (by weight) in the aforementioned mixes (see table 1). The main objective of phase I is to investigate the effect of different percentages of calcined clay incorporation on concrete mixes final strength.

Table 1.

Concrete mix designs for experimental investigation – phase I

	Control	**Mix #1**	**Mix #2**	**Mix #3**	**Mix #4**
Cement Weight	990	891	792	693	594
Sand Weight	2310	2310	2310	2310	2310
Water Weight	446	441	437	433	429
Cal. Clay Weight	0	90	180	270	360

- Phase II: four additional concrete mixes are developed to replicate the calcined clay incorporated mixes. However, calcined clay is not added. Thus, reduced cement contents were used in mix development (see table 2). The objective of this phase is to quantify the effect of the incorporated portion of calcined clay on concrete final strength.

Table 2.

Concrete mix designs for experimental investigation – phase II

	Mix #1	**Mix #2**	**Mix #3**	**Mix #4**
Cement Weight	891	792	693	594
Sand Weight	2460	2610	2760	2910
Water Weight	401	366	312	268

Concrete mixes were produced using high energy paddle mixer. Granular materials (cement, clay, and sand) were preblended for 2-minutes. Afterwards, water is added, and wet mixing continued for a duration of 5 minutes. Test specimens are prepared using standard 2 in. cube molds (see figure 3). Specimens were moisture-cured until their test dates.

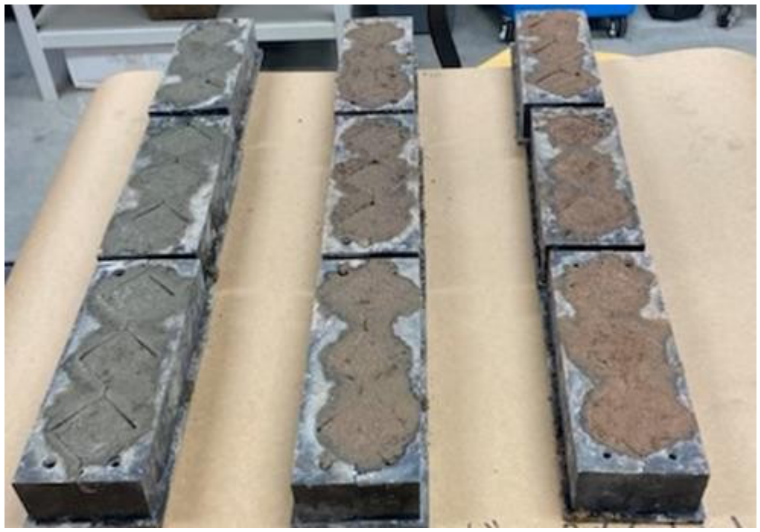

Figure 3. Standard 2 in. cube mold specimens for compressive strength testing

Concrete specimens were tested for compressive strength at ages 24-hour, 3, 7, 14, and 28 days (see figure 4).

Figure 4. Compression testing of concrete cube specimens

Phase I test results investigating the strength of calcined clay incorporate mixes versus the control specimens showed that calcined clay has positively enhanced the final compressive strength of concrete (see figure 5).

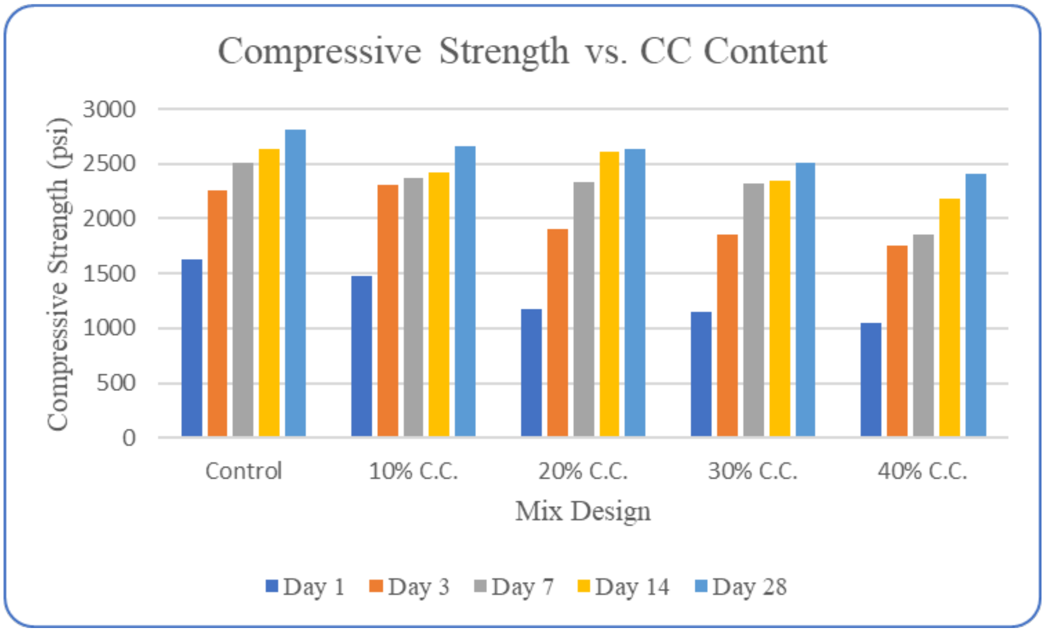

Figure 5. Compressive strength of concrete specimens versus calcined clay content

Phase II test results investigating the compressive strength of specimens using reduced cement content (in the absence of calcined clay) displayed a significant drop of hardened concrete compressive strength. This is an indirect indication of the calcined clay pozzolanic activity (see figure 6).

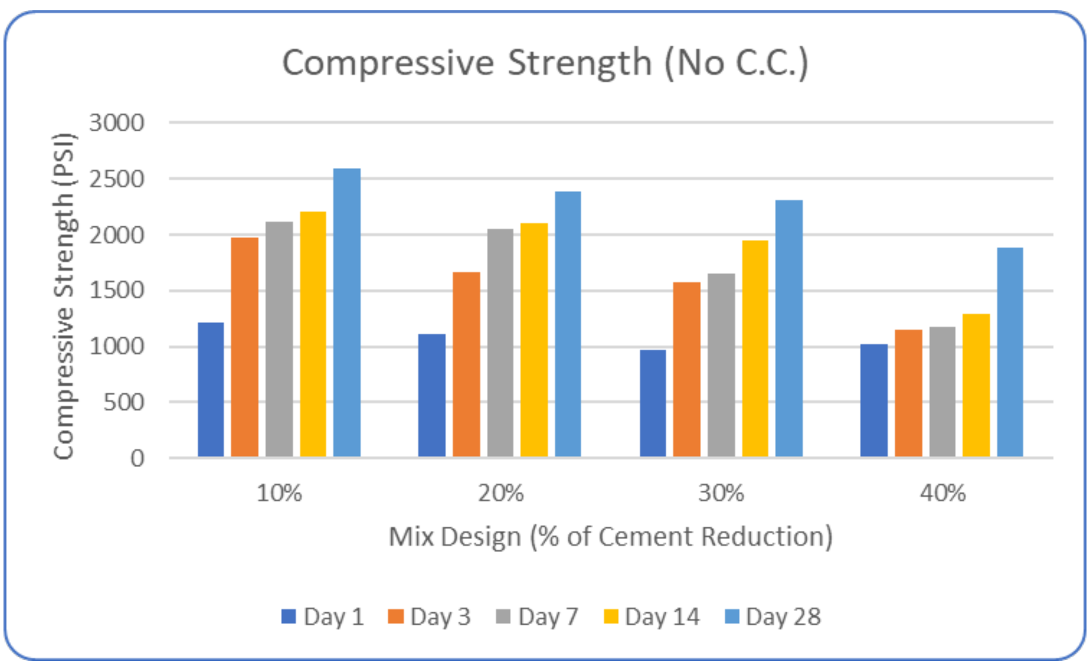

Figure 6. Compressive strength of specimens with reduced cement content (no calcined clay)

Conclusions

Dredged clayey material calcined using indirect rotary calciner at a temperature ranging from 750º C to 800º C (1292 F to 1472 F) displayed sufficient pozzolanic activity. Consequently, the calcined clay material could be successfully used in developing concrete mixes with lower cement content. Compressive strength test results showed that a calcined clay-concrete specimen with a 20% cement replacement would result in a higher final (28-day) compressive strength. Compressive strength testing showed that the pozzolanic effect of the calcined clay displayed increased efficiency after 14 days of concrete mixing. The use of calcined clay as proven in this research could significantly reduce the cement consumption in the construction industry. A 20% reduction in cement consumption will significantly reduce the carbon footprint of construction projects and result in additional LEED points for project certification.

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