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Use of metakaolin with stabilised extruded earth masonry units

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HIGHLIGHTS

- Small scale extruded bricks were manufactured under laboratory conditions.
- Bricks were tested in compression following dry and wet conditioning.
- Suitable compressive strengths with lime and metakaolin addition were achieved.
- Different stabilisation mechanisms with metakaolin, cement or lime and the soil exist.
- Interaction of the clay minerals varies but is key to strength development.

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ABSTRACT

Modern earth masonry increasingly utilises conventional methods of extruded fired brick production for the manufacture of unfired earth bricks. However, these bricks are not generally recommended for structural applications due to their loss of strength under elevated moisture contents. Disproportionate collapse could occur following accidental or intentional wetting of a 100 mm thick load bearing unfired earth wall. Unfired clay bricks can be chemically stabilised, typically by the addition of cement or lime to improve wet strength. However, the use of such binders has been shown to be ineffective for silt and clay rich soils used for extruded bricks.

The research presented in this paper demonstrates the change in compressive strength that can be achieved through the addition of metakaolin to cement and lime stabilised extruded earth masonry. Small-scale bricks were manufactured and tested in compression in both ambient environmental conditions and following a minimum of 16 h of full submersion in water. Though the addition of metakaolin did not universally improve performance. This research presents a feasible solution using 5% lime and 10% metakaolin, that would allow unfired extruded earth masonry units to be used for structural applications.

1. Introduction

There are growing concerns over the embodied environmental impact of construction materials [19]. Whilst earthen forms of construction have been used for thousands of years, there is a renewed interest due to its low embodied impact [13]. For this benefit to have a national impact modern methods of production and construction with earth are required. Modern earth masonry that uses commercial methods of brick manufacture can be utilised for unfired earth brick production [5,12,13].

Commercial extruded earth brick production uses the same methods of manufacture as fired brick units without the firing. This produces conventional sized bricks and results in a wall thickness of approximately 100 mm for internal partitions and inner leafs. Heath et al. [6] demonstrated the structural feasibility of unfired clay bricks for use in two to three storey domestic buildings, where lightweight concrete blocks, with a compressive strength of 2.9 MPa, would typically be specified. However, at elevated moisture contents the compressive strength of the units reduces which can lead to complete loss of structural integrity [5]. When unfired earth constructions are subjected to these conditions, even as an accidental case, then clearly disproportionate collapse could occur. This has led to a defined minimum strength criteria for the unfired brick units as 2.9 MPa under ‘dry’ conditions and 1.0 MPa under ‘wet’ conditions, where ‘dry’ conditions are under ambient temperatures and relative humidity and ‘wet’ conditions are following over 16 h being fully submerged in water [12].

Maskell et al. [12]performed a preliminary investigation into cement and lime stabilised extruded soil bricks. Stabiliser types

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and contents commonly used for compressed earth blocks were not always appropriate for extruded bricks, which typically had a higher clay and silt content than in compressed earth blocks. Cement and lime both increased the 'dry' and 'wet' compressive strength, with the performance depending on the mass fraction and initial curing temperature. While cement achieved greater 'dry' compressive strengths, the addition of lime achieved greater 'wet' compressive strengths. The addition of 5% lime, with an Initially Curing Temperature (ICT) of 105 °C achieved a 'wet' compressive strength of 1.02 MPa. Considering the variability of these results, the lower bound 95% confidence interval of this average strength is 0.85 MPa, therefore not meeting the minimum 'wet' strength criteria.

The performance of a stabiliser and the fundamental binding mechanism, may be improved by the addition of a secondary stabiliser or pozzolan. There has been growing interest in the use of industrial waste and by-products such as Ground Granulated Blast-furnace Slag (GGBS) and fly ash. Heath et al. [7] questions the future availability of slags and fly ash, as almost all of the slag is accounted for in Portland cement blends and fly ash production will dwindle in the UK due to a reduction in reliance on coal for power generation. Metakaolin is an alternative to GGBS and Pulverised Fly Ash (PFA) used within concrete manufacture based on Ordinary Portland Cement and geopolymers. Within the UK there are proven reserves of kaolin which could be used to produce approximately 1.4 million tonnes of metakaolin per annum [7]. Although the metakaolin is relatively highly processed material, its use and cost could be justified within large scale commercial manufacture where there are benefits of economies of scale.

The focus of this paper is the use of metakaolin as a secondary stabiliser for modern earth masonry units. The addition of various mass fractions of metakaolin to cement and lime stabilised extruded earth masonry units are described. Small-scale extruded bricks were manufactured using brick soil typically used for the commercial production of fired bricks, which has been shown to be a suitable representation of full-scale bricks. For the purposes of this paper, a successful stabilisation method is one that achieves a saturated or 'wet' compressive strength of 1 MPa, without the reduction of a 'dry' compressive strength tested in ambient conditions.

2. Background

2.1. Metakaolin

Metakaolin is a dehydroxylated form of kaolinite, following the chemical removal of the bonded hydroxyl ions from the kaolinite minerals, typically through heating to approximately 750 °C. As kaolin contains no carbonates, no CO_2 is released during heating leading to reduced embodied CO_2 in the final materials when replacing cement or lime. Due to the pozzolanic properties of metakaolin, there has been growing interest in its use as a cement replacement as well as an addition to lime or for geopolymer concrete [3,17,20]. Metakaolin has the chemical structure of $Al_2Si_2O_7$ and exhibits pozzolanic properties that can be potentially utilised to achieve the required strength criteria of extruded unfired earth bricks.

2.2. Stabilisation mechanisms

Metakaolin provides a source of alumina and silica for additional hydration reactions to occur in with both cement and lime. The reactions involving metakaolin for concrete applications have been reviewed by Sabir et al. [18]. The typical pozzolanic activation of metakaolin is with calcium hydroxide (CH) that is both the chemical make-up of hydrated lime and also a hydration product from Ordinary Portland Cement (OPC). In addition to this reaction Wild et al. [22] identifies that the metakaolin will accelerate the OPC hydration reactions as described later and act as a filler. It is expected that these reactions will be key for strength development for unfired earth masonry as demonstrated with more conventional concrete applications.

During the hydration of cement, 16–20% of CH, commonly referred to as Portlandite, is produced from the OPC [15]. Pozzolanic materials, such as metakaolin, can react with the CH to produce addition cementitious gels. Murat [14] presents three competitive hydration reactions between metakaolin and CH that produce calcium silicate hydrate (C–S–H) gels as well as calcium aluminate hydrate (C–A–H) and alumino-silicate hydrates that yield similar properties to Portland Cement [1]. Reactions between metakaolin and tricalcium silicate (C_3S) and tricalcium aluminate (C_3A), also present within cement, were investigated by Ambroise et al. [1]. While no effect on C_3A was identified, the presence of metakaolin was shown to accelerate the hydration C_3S up to a ration of C_3S:metakaolin of 1.40 with additional metakaolin acting as a filler. The same study also shows that calcium, alumina silica hydrates can precipitate within pore spaces that help to increase durability.

Sabir et al. [18] comment that there is minimal strength gain for more than 15% metakaolin replacement of binder mass. The acceleration of pozzolanic reactions is typically utilised for early strength development of concrete [18]. Variations in initial curing temperature, similar to used by Maskell et al. [12] for stabilised extruded earth masonry units development, have been shown to have a significant influence; with the increase in curing temperature to 50 °C permitting a reduction of 50% of the amount of metakaolin required to achieve optimum performance [18].

The reaction of metakaolin and lime in water has been discussed by Cabrera and Rojas [2] and Konan et al. [10]. Konan et al. [10] note that the reaction between metakaolin and lime forms CSH gel and aluminate phases, in accordance with the reaction with Portlandite as expected. In addition to the pozzolanic reactions that occur, the lime will also carbonate with Cabrera and Rojas [2] and Fortes-Revilla et al. [4] both commenting that the reaction kinetic varies depending on differing temperature and relative humidity and will result in differing properties depending on which reaction is dominant.

How these reactions between cement or lime and metakaolin are influenced by potentially reactive aluminosilicate natural clay minerals is not described in the scientific literature. However, the increase in the production of cementitious gels that can at least encapsulate the clay particles, treating them as effectively very fine aggregate in a cementitious matrix is expected to improve the mechanical properties and in particular the water resistance of the masonry unit. Maskell et al. [12] commented that a reaction between lime and the clay minerals resulted in the improved 'wet' strength compared to the cement. While the addition of metakaolin will increase the quantity of cementitious materials, if the lime and metakaolin react preferentially without the incorporation of the clay minerals, then this may result in reduced strength and water resistance, both of which are undesirable.

Due to the potential of metakaolin to improve the mechanical and durability properties of extruded unfired stabilised bricks, its use as a secondary stabiliser is investigated in this paper. While much of the previous work has focused on replacement of OPC, this study will consider it as a secondary stabiliser. The interaction of the soil both physically and chemically with the primary stabilisation additive affects its performance, as discussed by Maskell et al. [12] and the presence of uncalcined kaolin and other clay minerals may affect performance. The literature regarding the use of metakaolin for strength and durability have focused on the manufacture of either non-specific binders or concretes [18]. Although