Construction and Building Materials 52 (2014) 294–305

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanisms of strength development in masonry units using blended organic binders

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HIGHLIGHTS

- Glycerol and cooking oil can be used as a blended binder.
- Glycerol works as a lubricant to help with the even distribution of cooking oil.
- Packing, filling effect and hardening process contribute to strength of sample.
- No inorganic chemical process involved in strength development.
- Binding mechanism is due to binder encapsulation.

ARTICLE INFO

Article history:
Received 18 May 2013
Received in revised form 11 November 2013
Accepted 12 November 2013
Available online 5 December 2013

Keywords:
Glycerol
Cooking oil
Oxidation
Hardening
Strength development
Masonry
Organic binder
Waste utilisation

ABSTRACT

In this paper, there will be a discussion of the mechanical mechanism of strength development in a novel masonry unit. The aggregates used to produce the samples were chosen from the following: Pulverised Fuel Ash (PFA), Incinerator Bottom Ash (IBA) and Natural gravel and sand. The binder was a blend of clean cooking oil and pure glycerol combined using the ratio of 1:3 by weight. The units were manufactured using a compaction pressure of 8 MPa and a curing regime which involved heating the samples for 96 h at a temperature of 160 °C in a convection oven. X-ray diffraction (XRD) was used to analyse the chemical composition of the inorganic compounds and to identify any changes in these compounds due to curing. Energy-dispersive X-ray spectroscopy (EDS) was used to investigate the chemical element distribution in the samples helping to identify the binding mechanism in this novel unit. In addition, the micro structure of the sample was analysed using a scanning electron microscope (SEM). Results from the study show that the material distribution; the creation of a filler-binder paste; and the bonding provided by curing the mixture of cooking oil and glycerol play an important role in the strength development of samples. Also, it was found that after being thermally cured, these two immiscible liquids appeared to work together producing an effective binding effect that creates samples with high compressive strengths.

1. Introduction

Previously, it has been shown that bitumen [1,2] and more recently waste cooking oil (WCO) can be used as a binder for masonry units [3]. In the latter work, 5% WCO was added to a mix of limestone aggregates and after the mix was moulded, compacted at 4 MPa and cured for 12–48 h at 160 °C, compressive strengths of between 14.2 MPa to 30.7 MPa were obtained. The limestone aggregates used in that investigation can be classed as traditional aggregates, i.e. those which are excavated from a quarry. However, one of the benefits of using alternative organic binders such as WCO is that it is possible to entirely replace traditional aggregates with recycled aggregates, thus creating a unit which is composed of 100% waste materials [4]. This is something that cannot widely be achieved in traditional construction materials as the binding in these traditional materials relies on a certain degree of chemical bonding and the chemical interaction between the traditional binders and waste aggregates tends to be detrimental to the performance of the material. When using organic binders, the binding mechanism is mainly thought to be an encapsulation process (with possibly some very minor chemical interaction, which has an insignificant effect on the properties). Recycled aggregates do, however, tend to possess higher absorption properties than traditional aggregates and, hence, when used previously, a greater percentage of WCO was required (typically 12% WCO) [4]. Although this volume of oil is realistic in terms of a typical binder quantity it is

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http://dx.doi.org/10.1016/j.conbuildmat.2013.11.053

considered too high from a commercial perspective, as waste cooking oil (virgin and recovered) is becoming more expensive (450–500 GBP/tonne) due to, for instance its use in biodiesel production.

Interestingly, one of the major by-products of biodiesel production is waste glycerol. Generally, when 100 kg of biodiesel is produced, an estimated 10 kg of crude glycerol is generated [5]. In 2008 the total production of biodiesel in the 26 European countries was 9,570,000 tonnes, to which the UK contributed 145,000 tonnes (1.5% of the total) [6]. Due to the increase in production of biodiesel in recent years, a huge amount of crude glycerol has been generated, effectively swamping the market. Crude glycerol produced from the biodiesel industry has turned from a valuable product to a waste material and the price of crude glycerol has dropped dramatically (by up to a factor of 10) resulting in the closure of many conventional glycerol refineries [7]. Disposal of biodiesel by-products may also be a problem [8]. Thus, a new application for waste glycerol is required.

Chemically speaking, glycerol forms the 'backbone' of vegetable oils or WCO (i.e. triglycerides). Although in theory glycerol is immiscible with CO or WCO it could potentially act as a transport mechanism to help distribute the WCO during mixing. Glycerol is only slightly denser than water but has similar viscosity characteristics at room temperature (i.e. it possesses low viscosity or is 'thin') and so it may also help to reduce the absorption properties of the recycled aggregates. Ultimately, its use may help to reduce the required quantities of WCO, perhaps down to the levels seen in units made with the traditional limestone aggregates (i.e. 5%). Such a blended binder would be significantly cheaper than using a binder of WCO only.

Therefore, in order to further promote the use of alternative organic binders, two of the objectives of this paper are to:

(1) Investigate a method of reducing the WCO content in mixes containing 100% recycled aggregates (this involves the use of glycerol to facilitate better distribution of the oil) and;
(2) Investigate the hypothesis that the binding mechanism is one of encapsulation (an examination of the aggregate composition before and after the binding process will be performed to identify any changes in the aggregate due to the interaction with the binder and the manufacturing process).

Investigations carried out by Vu [9] showed that a blend of virgin cooking oil (CO) and glycerol (1:3; typically 5% CO: 15% glycerol) as a binder can be used to produce a unit containing 100% recycled aggregates. The compressive strength of these units was over 30 MPa. The water saturated compressive strength was over 8 MPa, which is still higher than the compressive strength of current concrete blocks used in the UK (i.e. 7 MPa) [10]. Comparative studies using water and CO as a binder were not as successful, as the compressive strength obtained was only 5.20 MPa. There is therefore a suggestion that the glycerol does not simply act to transport the WCO more efficiently and to negate the absorption of the aggregates but that it also adds to the strength development of samples made from these blended binder mixes. A third objective of the paper is therefore to:

(3) Investigate the mechanism of compressive strength development of the samples; the hypothesis is that the strength is significantly dependent on the packing of the aggregate particles; the absence of any interfacial transition zone (ITZ) [11], typically present in cementitious mixes; and the formation of a paste, composed of binder and filler aggregate particles which bind the coarse particles together.

Objective (3) predominantly involves a physical examination of the mix matrix. No attempt was made to investigate the changes in the organic chemistry of the blended binder itself (these have been performed elsewhere [12]). To best quantify these 3 objectives, any influence of the impurities found in WCO and waste glycerol were negated by using CO and pure glycerol for this investigation. Although previous comparisons between samples made from WCO and CO have shown no real difference in compressive strength (an easily measureable property which acts as a good indication of other physical performance properties of the samples [9]), it was thought that these impurities may disguise unnecessarily the mechanisms being quantified.

2. Materials and methods

2.1. Materials

2.1.1. Binders

2.1.1.1. Cooking oil. The binder used in this investigation was a blended binder composed of clean cooking oil and pure glycerol with the mixing ratio of 1:3 [9]. Pure glycerol was obtained from ReAgent Company, Cheshire, UK and the clean cooking oil (Rape seed oil) was obtained from Leeds University Catering Service; it originally came from the KTC Company, Wednesbury, West Midlands, UK. Fig. 1 shows a cooking oil sample after being thermally cured at 160 °C for 24 h in a petri dish, together with its scanning electron microscope (SEM) image. It can be seen that after thermal curing, the cooking oil became a 'jelly' like compound that could be manually 'fractured' forming the sticky 'jelly' fragments (to be clear, the sample was not brittle). This finding will be referred to later when the binding mechanism is discussed. The hardening process of cooking oil has been reported by Heaton et al. [12]; their investigation confirmed the importance of the presence of oxygen in the curing process. This layer of oil (Fig. 1) is about 1.5 mm thick. However, the thickness of the binder thin film in the material matrix is much less, typically 3.54 μm in samples made with glass powder filler and 15% cooking oil [4]. Heaton [4] also stated that, the thinner the binder film, the shorter the curing time needed. Although in the material matrix, oxygen cannot freely flow through the sample (resulting in longer curing times), the thinner binder film may become harder and more brittle compared with the thicker binder layer after curing shown in Fig. 1. As such, mechanically, the masonry unit would possess an elastic–brittle strain behaviour rather than a viscous or elastic–plastic strain behaviour (as indicated by Fig. 1). This is discussed later.

2.1.1.2. Glycerol. Glycerol (or 1, 2, 3, propanetriol) [13] is a simple polyol compound. It has three hydroxyl groups that are responsible for its solubility in water and its hydrophilic nature. Glycerol forms the backbone to all lipids i.e. triglycerides [14]. Therefore, glycerol is considered as a humectant or desiccant. Fig. 2 shows a glycerol molecule. In this study, only pure glycerol was used in order to investigate the binding mechanism of the blended binder.

When heating glycerol to the temperature of 160 °C, it was expected that the glycerol would undergo dehydration, forming a polarised compound (see Fig. 3). This dehydration will allow it form better bonding forces between the binder and/or aggregate and filler particles. However, the dehydration of glycerol will also increase its affinity for water.

When pure glycerol was heated in a petri dish the glycerol evaporated leaving no visible residue. This was not unexpected [9]. However, when considering the blended binder in a petri dish, the components of the blend very quickly separated out with the lighter oil floating on the denser glycerol. The glycerol was therefore prevented from evaporating and on heating a 'sticky' compound (different to that seen in Fig. 1) was formed at the interface of the oil and glycerol. This compound is thought possibly to suggest how glycerol may enhance the stickiness of the heated binder.

2.1.2. Natural sand and gravel

Natural sand (<5 mm) and gravel (5–10 mm) were used as aggregates to produce the samples used for microstructural investigation. All the natural aggregates were supplied by Tarmac Roadstone, Wolverhampton, West Midlands, UK. The mixing ratio of natural sand to gravel was 70/30. This ratio was chosen as it was similar to the fine to coarse aggregate ratios found in the IBA sample (see Section 2.1.3), with which the sand/gravel mix was compared.

2.1.3. Incinerator Bottom Ash (IBA)

The Incinerator Bottom Ash (IBA) used in this study was collected from Eastcroft Energy from Waste Facility (EC-EfW) – Waste Recycling Group (WRG) – Nottingham, UK. This facility processes about 160,000 tonnes of household waste generating about 45,000 tonnes of IBA each year. Two basic particle sizes, 5–10 mm and <5 mm were chosen; 70% of the IBA aggregate was 5–10 mm and 30% was <5 mm. This ratio is the same as the 'natural' ratios found in the collected IBA material. Table 1 shows the typical chemical composition of IBA collected from EC-EfW.