Available online at www.sciencedirect.com

ScienceDirect

Journal of the European Ceramic Society 34 (2014) 1341–1351

www.elsevier.com/locate/jeurceramsoc

Fibre reinforced lightweight aggregates

Markus Bernhardt [a], Hilde Tellesbø [a,b], Harald Justnes [a,c], Kjell Wiik [a,*]

[a] Department of Materials Science and Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
[b] Weber Leca Rælingen, NO-2008 Fjerdingby, Norway
[c] SINTEF, Building and Infrastructure, NO-7491 Trondheim, Norway

Received 3 May 2013; received in revised form 5 November 2013; accepted 11 November 2013
Available online 4 December 2013

Abstract

Carbon steel fibre reinforced lightweight aggregates (LWA) were produced in a pilot scale rotary kiln. Narrow size fractions as well as not-sieved (as received) material were investigated according to European standards with a main focus on strength and density and compared to a reference material without fibres. Depending on the size of the pellets a fraction of the fibres oxidized during firing. A strength increase proportional to the amount of non-oxidized fibres within the pellet was observed. The crushing resistance for as received fibre reinforced pellets (bulk density 452 kg/m^3) was 3.0 MPa corresponding to an increase in strength of 140%. The enhanced strength was also confirmed by the single pellet compression test.

Keywords: Lightweight aggregate; Fibre reinforcement; Mechanical properties; Crushing resistance; Strength

1. Introduction

Lightweight aggregates (LWA) are commonly utilized as aggregate for lightweight concrete, insulation material for road constructions or in lightweight brick production.[1–3] Raw materials for LWA can be of artificial or natural origin.[4–9] Constant needs for stronger and lighter materials give the motivation of modifying and improving the properties of lightweight aggregates. LWA are highly porous, almost spherical particles that consist of a glassy matrix incorporating various types and amounts of crystalline inclusions. Consequently the material can be characterized as brittle and thus susceptible to brittle failure. A common way to improve the mechanical properties of brittle materials like ceramics or concrete is reinforcement with fibres. Various factors influence the success and degree of the fibre reinforcement: The difference in elastic-modulus between fibre and matrix as well as the strength-, distribution- and dimension of the fibres and the interfacial bond between fibre and matrix.[10]

In the present investigation steel fibre reinforced lightweight expanded clay aggregates were produced and examined with a special focus on density and strength. A detailed determination of the strength of single LWA pellets requires the knowledge of the porosity, the density of the matrix phase and some geometrical factors of the sample as pointed out by Bernhardt et al.[11] All physical properties of the fibre containing LWA were compared to a reference material without fibres produced in the same way as the fibre reinforced samples. In this investigation the effect of fibre reinforcement on the strength of LWA-pellets is reported and possible toughening mechanisms are put forward and discussed.

2. Materials and methods

2.1. Raw material and LWA manufacturing

Fibre containing lightweight aggregates were produced in a pilot scale rotary kiln. The raw material was clay blended with 1 wt.% waste motor oil as expansion agent and carbon steel fibres of 1–2 mm length and approximately 30 μm diameter. Homogenization of the clay as well as the mixing of oil into the clay was performed by shaft mixers in an industrial production line at Saint-Gobain Weber in Norway. The fibres were supplied by the Swedish company "Ocklebo stål" and are made from

* Corresponding author at: Department of Materials Science and Engineering, Norwegian University of Science and Technology, Sem Sælands vei 12, 7491 Trondheim, Norway. Tel.: +47 73594082.
E-mail addresses: kjell.wiik@ntnu.no, kjell.wiik@material.ntnu.no (K. Wiik).

0955-2219/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jeurceramsoc.2013.11.009

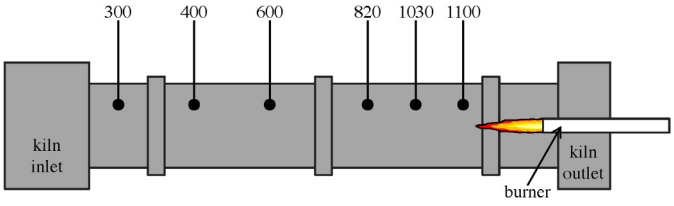

Fig. 1. Temperature profile in °C of the rotary kiln. The dimensions of the kiln are 10 m length and 0.3 m diameter.

milled steel wool. Mixing the fibres into the clay as well as the homogenization and granulation of the material were executed in an eirich mixer. Dried clay powder was mixed with steel fibres before wet (approx. 20% water content), oil containing clay and additional water (to reach sufficient plasticity to form pellets) was added. After homogenizing the mass was pelletized to granules of irregular size. Particles with diameters above 10 mm were removed before firing. The total fibre content of the material was 11.5 wt.% (approx. 4.5 vol.%) of the dry clay. LWA pellets without fibres were produced as a reference material using the same production procedure. The mineralogical and chemical composition of the raw clay was determined by an external research company called "IBU-tech advanced materials AG" using gravimetry, wet chemical quantification methods and X-ray diffraction.

The granulate material was fired in a continuous process in a direct heated (natural gas) rotary kiln of 10 m length and 0.3 m diameter. The approximate temperature distribution in the kiln is given in Fig. 1. Feeding of the kiln was executed by a dosing belt with a throughput of approximately 30 kg/h and the dwell time of the material in the kiln was about 30 min. Maximum burning temperatures varied from 1120 °C for the reference material to 1090 °C for the fibre containing material. The finished material was deposited on metal plates for initial cooling and thereafter put in metal drums and cooled to room temperature.

2.2. Material testing

The diameter after firing of the LWA pellets ranged from fine dust up to 15 mm for both the reference- and fibre-containing material. The following tests were performed on as received (not sieved) material.

Oven dried particle density and water absorption after 24 h according to EN 1097-6.[12]

The loose bulk density (defined in Ref. 13) by measuring the mass of 1 litre of bulk material.

Crushing resistance according to EN 13055-1;[14] This standard test is executed with a sieving fraction of 4–22 mm.

Particle size distribution according to EN 933-1[15] using the following mesh widths (given in mm): 31.5, 14, 12.5, 10, 8, 6.3, 4, 2, 1, and 0.5.

Further tests were executed with the following size fractions (sieved): 1–2 mm, 2–4 mm, 4–6.3 mm, 6.3–8 mm, 8–10 mm and >10 mm. Each sample consists of several individual pellets and the amount of tested pellets is given in Table 3. Samples are denoted as Ref- and Fib- where Ref- is the reference material without fibres and Fib- is the fibre containing material. The numbers represent the size fraction in mm (example: Fib-8–10 is the fibre containing material of the fraction 8–10 mm).

The average dry particle density, $\rho_{particle}$, of each sample was determined by sand pycnometry. Between 120 and 4700 individual pellets (depending on size) were put into a flask and covered with a known amount of fine sand to measure the volume. The particle density was calculated by dividing the mass of the material by the measured volume.

Helium pycnometry was used to determine the density of the matrix phase, ρ_{matrix}. Each density measurement was performed by milling a couple of pellets to a particle size <36 micron and subsequently assessing the density in an AccuPyc 1330 helium pycnometer from micrometics. The average porosity, P, in per cent of each sample is calculated by Eq. (1).

$$P = 100 \cdot \left(1 - \frac{\rho_{particle}}{\rho_{matrix}}\right) \tag{1}$$

Single pellet strength was determined by uniaxial compression between 2 parallel rigid platens. The diameter of every single pellet was measured with a calliper before the granule was placed on the bottom plate of a press. Due to deviations from spherical geometry the diameter was measured between the highest and the lowest point when the pellet was lying in a stable position. Compression was performed with a constant speed of displacement of 2 mm per minute until a crack ruptured the pellet into at least two pieces. The applied load at failure, F_{crit}, of at least 50 pellets was recorded for each sample. The test equipment was a press made by "Instron®" coupled to a load cell with a maximum capacity of 1 kN. The platen material was alumina. The solid strength, σ_{crit}, of each sample was calculated from the average load at failure, F_{crit}, the volume fraction of solid material, $\rho_{particle}/\rho_{matrix}$, and the average diameter, D, using Eq. (2).

$$\sigma_{crit} = \frac{F_{crit}}{D^2 \cdot (\rho_{particle}/\rho_{matrix})^{2/3}} \tag{2}$$

Eq. (2) gives a strength value which is independent of the total porosity, P.[11]

Prior to brittle failure, all pellets will suffer a certain "crumbling" at the contact point between platens and pellet. The radius, a_c, of this "crumbled area" at the point of failure is important for the calculation of stress distribution and can be approximated from the average anvil displacement at failure, x, and the initial average radius of a sample, R, by Eq. (3) assuming a perfect sphere and equal damage/crumbling at the top and at the bottom.[11]

$$a_c = \left(R^2 - \left(R - \frac{x}{2}\right)^2\right)^{1/2} \tag{3}$$

Additionally to the single pellet compression test the crushing resistance, C, according to EN 13055-1[14] was determined for the fractions 2–4 mm, 4–6.3 mm, 6.3–8 mm, and 8–10 mm for both the reference and the fibre containing material. The loose bulk density, ρ_{bulk}, of the same samples was determined prior to the crushing resistance test.