Construction and Building Materials 167 (2018) 271–285

Contents lists available at ScienceDirect

Construction and Building Materials

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

The durability and environmental properties of self-compacting concrete incorporating cold bonded lightweight aggregates produced from combined industrial solid wastes

P. Tang [a,b,*], H.J.H. Brouwers [a]

[a] Department of the Built Environment, Eindhoven University of Technology, 5612AP Eindhoven, The Netherlands
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

HIGHLIGHTS

- Cold bonded lightweight aggregates (CBLAs) are produced from combined industrial wastes.
- Fine incineration bottom ash has been largely recycled in CBLAs.
- Durability of self-compaction concrete with CBLAs are evaluated.
- The SCC with three types of CBLAs complies with environmental legislation.
- A closed recycling loop of industrial solid wastes can be achieved.

ARTICLE INFO

Article history:
Received 4 July 2017
Received in revised form 8 November 2017
Accepted 6 February 2018

Keywords:
Combined industrial solid wastes
Artificial aggregate
Pelletization
Self-compacting concrete
Durability
Environmental impact

ABSTRACT

Several industrial solid wastes are integrally recycled to produce cold bonded artificial aggregates (CBLA) using the pelletizing technique, and incineration bottom ash fines (BAF, 0–2 mm) are innovatively used to strengthen the pellet strength. Three types of CBLAs are produced, in which BAF, nano-silica produced by olivine dissolution and polypropylene fibre are applied to improve the aggregates' properties (strength, etc.), respectively. The influence of these different types of CBLAs on the designed self-compacting concretes (SCCs) are experimental study and compared. The fresh and hardened properties of the concrete with and without CBLAs are investigated, including slump flow diameter, t_{500} time, V-funnel time, bulk density, flexural and compressive strength, etc. Moreover, the durability of the concretes is studied through water penetration and freeze-thaw tests. Additionally, the leaching behaviour of heavy metals and salts from the concretes are evaluated through different leaching tests according to environmental legislation. The results show that the roundish particle shape of CBLAs benefit the flow of concrete in fresh stage, and the strength of concrete with CBLAs has linear relation with its bulk density, and the cumulative mass loss profiles during freeze-thaw tests were influenced by the types of CBLAs. The leaching tests show that the concretes containing CBLAs are environmental non-hazardous.

1. Introduction

Construction and industrial solid wastes are nowadays attracting worldwide attention regarding to their dispose, or recycle and reuse as secondary resource [1,2]. The application of recycled concrete aggregates as alternative aggregates in construction field has been reported widely and promoted successfully [3,4]. The industrial solid wastes also have been used as building materials in recent years. For instance, coal fly ash (FA) from coal-fired power plants is generally used as filler or pozzolanic materials [5,6], and combustion bottom ash can be used as aggregates in concrete [7]. Municipal solid waste incineration (MSWI) bottom ash has been used as aggregates in concrete [8,9]. Paper sludge ash (PSA) from paper industry is reported to be used as pozzolanic additives or to produce hydrophobic concrete [10,11]. Washing aggregate sludge (WAS) from aggregate production has been used to produce lightweight aggregates under high temperature [12]. The MSWI bottom ash is a dominant by-product in waste-to-energy plant for the management of municipal solid waste and further treatments are needed to remove the salts and heavy metals from bottom ash to make its leaching properties comply with the legislation [13]. However, it is reported that these treatments have less

* Corresponding author at: Department of the Built Environment, Eindhoven University of Technology, 5612AP Eindhoven, The Netherlands.

E-mail address: p.tang@tue.nl (P. Tang).

https://doi.org/10.1016/j.conbuildmat.2018.02.035
0950-0618/

efficiency on the fine fractions of MSWI bottom ash which contains higher amount of contaminants than the coarser fraction (>4 mm), hence, this fine MSWI bottom ash remains an issue that needs research.

It is worth to mention that those industrial solid wastes have their own intrinsic properties which may cause negative influence in application while might bring benefit in other situations. For instance, the presence of metallic aluminium in MSWI fly ash leads to the generation of hydrogen when used in concrete, which decreases the strength of concrete products [14], while when used in autoclaved aerated concrete, the metallic aluminium can be used as aerating agent [15]. Therefore, it is of interest to figure out the integral recycling possibility of these industrial wastes, in a way to transfer their drawbacks into benefits.

Pelletization techniques have been applied as a way to recycle the powdered wastes for producing artificial lightweight aggregates under high temperature with foaming agent or at room temperature with binders [16,17]. The production of artificial lightweight aggregates by a cold bonding pelletization technique based on solid wastes has been studied and reported in literature [18–22]. By using this technique, the industrial solid wastes can be recycled and reused to decrease the demand of space for landfilling; meanwhile, an artificial lightweight aggregate can be produced which could be used as aggregates in concrete, subsequently, the consumption of limited natural resource for aggregates can be reduced; in addition, most of the industrial solids contain contaminants (salts or heavy metals) which may pollute the environment and need to be stabilized before disposal, pelletization of these wastes with proper binders to produce artificial aggregates is a way to combine stabilization treatment and recycle of solid wastes. Hence, it is a promising method for the reuse and recycle of increasing industrial solid wastes. However, in most of the cases, unitary raw waste material (mainly powders) is used for pelletization except the binder [17] and the industrial solid wastes are produced daily and proper way to dispose them is in demand. On the other hand, these wastes can be very beneficial if being used in proper way. Hence, an integral recycle/reuse of those industrial wastes is of importance to be considered applying the pelletization technique.

The properties of the artificial aggregates have significant effects on their application in concrete as gravel replacement [23], and the crushing strength of the artificial aggregates is partially related to the strength of the concrete products. Therefore, methods for increasing the aggregate strength were studied [17,21]. It is addressed that the increasing of binder amount or curing under streaming condition can result in higher aggregates strengths [24]. However, there are rather few other methods for improving CBLA properties.

Hence, the main goal of this research work includes the recycling of combined industrial solid waste innovatively to produce cold bonded lightweight aggregates (CBLAs) and improving the properties of the produced aggregates. The methods of improving the pellets are: (1) use of MSWI bottom ash fines (BAF, 0–2 mm) to improve the skeleton strength of pellets; (2) adding polypropylene fibre (PPF) as reinforcement of the pellets; (3) applying nano-silica (nS) as binder replacement.

Several types of industrial solid wastes in the Netherlands are recycled integrally to produce CBLA by applying the pelletizing technique. Three types of CBLAs are produced with consideration of improving their aggregates' strength, including the use of BAF, nano-silica from olivine dissolution and polypropylene fibres. The properties of these CBLAs are evaluated and compared with the ones produced by others in literature. Subsequently, these CBLAs are used in self-compacting concrete to replace natural gravels and to study their influences on the concrete properties related to the properties of the CBLAs. The fresh and hardened properties of the concretes are tested and the durability properties of the concretes are studied through the water penetration and freeze-thaw tests. Finally, the environmental impact of the concretes with artificial aggregates are evaluated using two types of leaching tests and results are compared with the Dutch legislation.

2. Materials and experimental methods

2.1. Raw materials and their characteristics

The cement used in this study is CEM I 42.5 N (OPC) provided by ENCI (the Netherlands) for the production of aggregates and concrete mixtures. The powder coal fly ash (FA) used is obtained from a Dutch power plant and paper sludge ash (PSA) from a Dutch paper recycle company. The washing aggregate sludge (WAS) is provided by a gravel production company (Smals, the Netherlands). The municipal solid waste incineration (MSWI) bottom ash fine fractions (BAF, 0–2 mm) is provided by a waste-to-energy plant in Moerdijk (Attero, the Netherlands) by directly sieving from the bottom ash heap in the plant. The polypropylene fibre (PPF) with a length of 3 mm, density of 0.91 kg/m^3 is provided by FBG (the Netherlands) and Bonar (England). The nano-silica used in this study is the same as applied in [25] and [26] produced by olivine dissolution. The sand (0–4 mm) and gravels (2–8 mm and 8–16 mm) used for concrete are provided by Smals (The Netherlands).

The chemical compositions of the materials are measured by X-ray fluorescence (XRF) and the crystalline phases present in the materials are detected by the X-ray diffraction (XRD, Cu tube, 40 kV, 30 mA, 3–75°, 0.02°/step, 0.2°/min). Table 1 shows that the main chemical compositions of all the materials used belong to the SiO_2-CaO-Al_2O_3-Fe_2O_3 system. WAS contains mainly SiO_2, and a considerable amount of Al_2O_3 and Fe_2O_3, and PSA consists high amounts of CaO, and SiO_2 and Al_2O_3. The main chemical compositions in FA and BAF are SiO_2, Al_2O_3 and Fe_2O_3. Fig. 1 shows the crystalline phases in PSA, FA, WAS and BAF. It is detected that the main crystalline phases in WAS are quartz, magnetite, clay minerals of the chlorite family, and feldspar; in PSA there are calcite, portlandite, gehlenite, and calcium silicate found. FA consists of quartz and mullite, and BAF contains quartz, calcite, hematite, feldspar and anhydrite.

The particle size distributions (PSDs) of the powder materials are measured using laser diffraction (Mastersizer 2000 Malvern) and the PSD of the particle aggregates is measured following EN 933-2 [27]. A helium pycnometer (AccuPyc II 1340) is applied to measure the specific densities. The PSDs of the materials for producing aggregate are shown in Fig. 2 and their densities are listed in Table 1.

2.2. Artificial aggregates production and their properties

The artificial aggregates are produced using a disc pelletizer, which has a pan diameter of 100 cm and collar height of 15 cm as shown in Fig. 3(a). The vertical angle of the pan is 45° and the running speed is 15 rpm during the process. The raw materials used for the aggregates are firstly mixed homogeneously and then around 10 kg of the mixed materials are put on the running disc (Zone 1 in Fig. 3(a)). After around 5 min of running, about 2 kg of water is sprayed continuously on to the materials in the pan and then they are running again for 10 min. The next running cycle starts with the addition of another 10 kg of mixed materials to the running pan (Zone 1), and the rounded artificial aggregates from the last round will drop off automatically from the left lower corner of the pan (Zone 2 Fig. 3(a)). The freshly produced aggregates (Fig. 3(b)) are sealed in plastic bags for further use and tests.