Construction and Building Materials 174 (2018) 369–375

Contents lists available at ScienceDirect

Construction and Building Materials

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

Investigation into the properties of concrete modified with biomass combustion fly ash

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HIGHLIGHTS

- Biomass combustion fly ash are among the most promising of concrete components.
- Fly ash waste may be used for concrete by replacing upto 15% of cement.
- Fly ash additives can be used for modification of cementations systems.

ARTICLE INFO

Article history:
Received 29 January 2018
Received in revised form 29 March 2018
Accepted 13 April 2018

Keywords:
Biomass combustion fly ash
Concrete
Compressive strength
Porosity
Freeze-thaw resistance

ABSTRACT

Concrete is the most widely used construction material obtained after the setting of the mix composed of coarse and fine aggregates, cement and water. The main properties of concrete are determined by the quality and characteristics of aggregates, W/C ratio, and the uniformity of mix compaction. Compressive strength is one of the key characteristics of concrete. Materials used: Portland cement CEM I 42.5 R, 0/4 fraction sand, 4/16 fraction gravel, biomass combustion fly ash, superplasticizer, and water. Seven batches of specimens were made with different biomass fly ash content: 0%, 5%, 10%, 15%, 20%, 25%, and 30% (replacing cement in the mix, %). The following properties of modified concretes were tested: compressive strength, water absorption, density, ultrasonic pulse velocity, porosity (open and closed), and predicted resistance to freezing and thawing cycles. Concrete, where 15% of cement is replaced with biomass combustion fly ash, has higher density (2360 kg/m^3), compressive strength after 28 days (38.3 MPa), ultrasonic pulse velocity (4466 m/s), lower water absorption rate (3.72%) and higher closed porosity (2.54%). All these characteristics improve the freeze-thaw resistance of concrete. The tests revealed that concrete modified with 15% of biomass fly ash had better durability and freeze-thaw resistance characteristics and can be used in construction works. The obtained linear regression equations illustrate the relationships between the density, compressive strength after 28 days of curing, ultrasonic pulse velocity after 28 days of curing, and predicted freeze-thaw resistance of modified concrete.

1. Introduction

Different types of concrete are used in construction. Concrete has a wide range of applications as it is produced from locally available aggregates at relatively low cost. Aggregates make up to 80% of concrete volume. Concrete manufacturing is energy intensive industry. Energy is used in the production of raw materials, final products, and in transportation. Energy consumption must be minimised in all manufacturing stages and also by reducing the cement content in concrete. In spite of the great interest in waste recycling and recovery, ash is utilised at low levels. Germany and Japan utilise only 10% of ash and only 5% of ash is recycled in the USA. It is expected that recycling and recovery of ash will receive greater attention in the future [1].

Cement production from local mineral resources is energy intensive industry. The current global trend is to save non-renewable sources of energy and to obtain energy from renewable sources with lower environmental impact. However, the development of renewable energy industry and large-scale biomass incineration demand higher amounts of combustible raw materials. Biomass incineration plants burn logging waste, straw, and other biological waste and generate big amounts of incineration waste. Biomass incineration waste is mainly ash that is disposed in landfills.

Utilisation of biomass fly ash has become an acute problem. Tests with coal ash have proven that it can be used as a binder in

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https://doi.org/10.1016/j.conbuildmat.2018.04.125
0950-0618/

concrete to improve certain characteristics of concrete. Replacing a certain amount of cement with ash also reduces the cost of concrete products. Utilisation of ash in concrete manufacturing enables to reduce the amount of Portland cement in concrete and also to lower CO2 emission. The abatement of CO2 emission in cement industry is a priority axis in the European Union and in the world too.

Biomass incineration for energy production enabled to decrease the cost of energy production. However, high amounts of ash is generated in this process. Biomass incineration ash causes serious environmental problems. At present, a major part of this waste (25,000–30,000 tonnes of wood ash per year) is disposed in landfills in Lithuania. Research results demonstrate that such waste can be effectively recycled in the industry of construction products [2–8].

Chemical composition of biomass fly ash is a very important factor for its utilisation in concrete industry. This composition depends on different factors, such as biomass growing area and conditions, soil and biomass type, incineration parameters, etc. The chemical composition can vary across a very wide range [9–12].

Extensive research into industrial by-products and ash from agricultural materials, such as wood ash or rice husk ash, is conducted looking for possibilities to utilize ash as cement replacement in concrete. The current boom in construction industry has escalated the demand for cement, which is the main constituent in concrete. Cement industry is also one of the primary sources of carbon emissions and a major consumer of natural resources, such as aggregates. It is also energy intensive industry. Therefore, utilisation of biomass incineration ash solves a twofold problem: the disposal of waste and substitution of cement in concrete products [13–16]. Researchers had conducted tests that showed promising results proving that wood ash can be used to replace a certain part of cement in concrete products [17–19]. Thus, using biomass incineration ash in modified concrete helps to transform ash from an environmental concern to a useful resource for the production of a highly effective alternative cementing material [20].

Biomass incineration ash can be also used for the production of multi-purpose ceramic products [21–23] by introducing up to 50% of ash into the moulding mixes. The mixed samples were fired at 950 °C without the addition of additives. The results showed that water absorption increased and apparent density and compressive strength decreased with higher ash content. The authors state that the optimal amount of ash to be utilised in ceramic products manufacturing shall not exceed 20%. Other authors state that from 5% to 10% of biomass ash additive decreases the density of ceramic products by 210 kg/m^3, thermal conductivity up to 0.13–0.16 W/(m^2K) and increases water absorption by 7%. However, this ash must be additionally washed before recycling it for fired brick manufacturing, and the washing impedes the manufacturing process and increases the production costs [24].

Researchers tested the recycling of biomass ash in concrete manufacturing by replacing part of the cement with fly ash and found that the optimal replacement percentage is 10% by weight of cement. The highest compressive strength after 28 and 90 days of curing was observed in specimens containing 2.7% of fly ash by weight of the mix and from 0 to 21.7% of bottom ash by weight of the mix. Compared to the control specimens, the lowest result was observed in all batches containing 8.1% of fly ash where cement content was reduced to 18.8% [25].

Naik et al. investigated the effects of wood ash on freeze-thaw resistance of concrete [19]. Changes in relative dynamic modulus, pulse velocity and length were investigated. The replacement percentages 5%, 8% and 12% by weight of the binder were tested. There was no important effect on freeze-thaw cycles (300 cycles) and relative dynamic modulus of concrete mixes; thus it was concluded that incorporation of wood ash did not produce any significant difference in the relative dynamic modulus. The relative dynamic modulus of the control mix was 97.7%; it reduced to 95.7% in specimens containing 5% of wood ash, changed to 97.8% in specimens containing 8% of wood ash and to 95.7% in specimens containing 12% of wood ash by weight of the binder. Also, no significant effect was observed on ultrasonic pulse velocity with the incorporation of wood ash. In the control mix the pulse velocity was 5425 m/s, in specimens containing 5% of ash it was 5480 m/s, in specimens containing 8% of ash it was 5560 m/s and in specimens containing 12% of ash the pulse velocity was 5435 m/s.

Tests with concrete mixes containing river sand revealed that the mixes where calcium-rich wood ash was used as cement replacement had a higher water demand to obtain the suitable workability. Mixes with replacement percentages up to 16% by weight of cement were tested. The highest compressive strength values were recorded in specimens containing 8% of wood ash [26].

The paper by M. Limbachiya et al. presents the results of tests into the properties of concrete mixes made of sand, coarse aggregates and recycled concrete aggregate, where a certain proportion of cement was replaced with fly-ash. Researchers found that specimens with ash additive had better mechanical characteristics compared to the control specimens. The specimens were tested after 3, 7, 14, 28, 56, 91, and 365 days of curing. The authors claim that specimens containing ash additive had a lower W/C ratio than specimens without ash. A linear relationship between the compressive strength and the rate of carbonation was detected. Higher resistance to sulphate attack and thus better durability characteristics of concrete were also observed [27].

Porosity is a very important parameter for the durability of concrete. Freeze-thaw resistance of concrete mainly depends on capillary porosity and entrained air. These parameters are controllable in concrete manufacturing process.

There are four types of pores in the pore system of concrete: gel pores; capillary pores of 5–5000 μm in size; macropores resulting from entrained air and macropores resulting from insufficient compaction. Gel pores have a negative effect on concrete strength. Capillary pores and bigger pores reduce the strength of concrete [28].

It is generally known that low W/C ratio and appropriate curing conditions are the key factors for producing freeze–thaw resistant concrete products [29–32].

N. Asrara claims that amorphous silica dioxide provides corrosion protection and increases the strength of concrete by reducing porosity and participating in the building of CSH crystals through the reaction with calcium hydroxide. The reaction outcomes are the reduction of $Ca(OH)_2$ content and increase of C-S-H content, which improves the strength and durability of concrete [33].

2. Materials and research methods

CEM I 42.5 R type Portland cement complying with LST EN 197–1:2001 requirements was used in the tests. Characteristics and chemical composition of Portland cement are presented in Tables 1 and 2. Characteristics and chemical composition of biomass fly ash are presented in Tables 3 and 4. 0/4 fraction sand complying with

Table 1
Physical-mechanical properties of the cement.

Properties	Portland cement CEM I 42.5 R
Specific surface area, cm^2/g	3700
Particle density, kg/m^3	3200
Bulk density, kg/m^3	1200
Standard consistency paste, %	25.4
Initial setting time, min	140
Final setting time, min	190
Compressive strength after 7 days, MPa	28.9
Compressive strength after 28 days, MPa	54.6