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Utilization of waste glass in translucent and photocatalytic concrete

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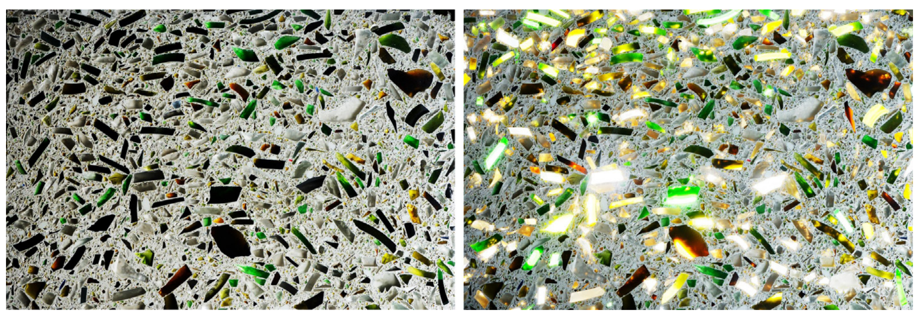
HIGHLIGHTS

- Waste glass is utilized to produce translucent and air purifying concrete.
- Waste glass-based concrete with good mechanical properties and suppressed ASR is developed.
- Air purification ability of concrete is enhanced by the glass particles.

GRAPHICAL ABSTRACT



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ABSTRACT

This article addresses the development of a translucent and air purifying concrete containing waste glass. The concrete composition was optimized applying the modified Andreasen & Andersen model to obtain a densely packed system of granular ingredients. Both untreated (unwashed) and washed waste glass fractions were utilized in concrete. The fresh and hardened concrete properties were investigated. In order to ensure a durable material, the expansion due to the alkali-silica reaction was also analyzed. Subsequently, concrete tiles of different thicknesses were produced and their translucency was quantified. Additionally, two different types of TiO_2 were utilized in concrete to analyze the glass aggregates effect on the photocatalytic degradation of air pollutants (NO and NO_2). The obtained results indicate that the developed concrete has satisfactory mechanical properties, coupled with good durability, translucency and enhanced air purification properties.

1. Introduction

Concrete is the mostly produced manmade material worldwide, reaching about 20–25 Gt of annual production [1]. The architectural possibilities, form flexibility, mechanical properties, durability and relatively low price are the main reasons for its common use. To produce such high amounts of concrete, a high amount of its ingredients is needed, especially fine and coarse aggregates, which in most cases exceed 60% of concrete's volume. The environmental legislations become increasingly strict over the last decade, new concepts and technologies of materials re-use after their primary service life are being constantly developed (e.g. for recycled concrete [2,3]); therefore the application of recycled or waste materials as concrete ingredients is being strongly promoted. Waste glass can be considered as one of the possibilities. It is a material that cannot be re-used for glass production due to its high chemical pollution and contamination with metal, paper, plastic, porcelain, etc. As a result, waste glass is often either landfilled or disposed in municipal dumping grounds. Furthermore, in most parts of the world the collection and recycling of glass are not well developed. In places where no local glass recycling facilities are available (e.g. Hong Kong [4]) all the collected

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glass is considered a waste material. There are several countries where the consumer packaging glass collection exceeds over 80% of the produced glass (e.g. Germany, Finland, Switzerland, Belgium, the Netherlands, Denmark, Austria, Sweden, Norway [5]) and where a significant majority of this glass is recycled. Nevertheless, even in these countries, the non-recyclable and waste glass constitute a growing problem which needs sustainable and innovative solutions. Therefore, among the possibilities offered by various industry sectors, the utilization of waste glass in building materials can be considered a sustainable solution. Moreover, such a solution can be economically attractive, as it could reduce the demand for conventional raw materials. Investigations on various applications of waste glass in building materials have been widely presented in the literature, e.g. in fired clay bricks [6], paving blocks [7], road applications [8], expanded-glass lightweight aggregates in concrete [9–12], as a binder blended with cement (milled glass) [13–16] or as a raw material in cement production [13,17]. Nevertheless, the waste glass is in most cases used in concrete. It is important to mention here, that majority of the available research considers only washed glass, which unfortunately demands an additional technological step in the concrete production process. Waste glass is available in many different size fractions, from a few micrometers (powder) up to a few centimeters, which makes it possible to replace conventional, mineral concrete aggregates and fillers (fines, sand, gravel) in concrete. As demonstrated in [18,19], broken glass could be used as sand replacement in concrete pavement, asphalt additive and road filler. Moreover, glass aggregate has been also used for the production of aesthetic and decorative concrete [20] because the exposed glass particles in polished surfaces are attractive for certain architectural and decorative applications. In addition to the application of glass aggregates in traditional concrete, research has been also performed on the development of architectural self-compacting concrete (SCC) using fine and coarse glass aggregates [4]. As a result, a decorative concrete (with exposed glass particles) with a complete replacement of conventional aggregates by glass has been produced, having the 28 days compressive strength of 40 MPa.

However, there are some potential issues related to the utilization of glass in concrete. Glass exposed to highly alkaline concrete pore solution is susceptible to alkali-aggregates reaction (AAR) or alkali-silica reaction (ASR), which leads to detrimental expansive ASR products [20–22]. The ASR-damage is a multiple-step, long-term process in which firstly the alkalis originating from cement react with water, producing sodium and potassium hydroxides. Then, the reactive silica present in glass slowly dissolves in the alkaline pore solution. Subsequently, the dissolved silica reacts with the alkali hydroxides, producing a viscous and unstable alkali-silica gel, which is able to imbibe water and swell [22–24]. Additional water enhances the gel development, inducing tensile stresses that lead to a slow concrete deterioration. One way to minimize the ASR risk is to limit the alkali amount in concrete pore solution by using low alkali cements. Suppression and neutralization of the reaction can be also obtained by utilization of pozzolans in concrete [21,23–31]. Pozzolanic materials are characterized by a high silica content and a high specific surface area. Pozzolans consume alkalis to form alkali-silicates, so that no alkalis remain in later stages to react and produce expansive ASR products. In the absence of pozzolanic additives, the reactive silica present in glass particles may slowly dissolve in the alkaline pore solution, react with alkalis and induce the ASR damage. It is important to emphasize that the glass particle size is crucial for ASR, as the glass powder (<300 μm) does not cause ASR issues and can be considered as a pozzolan [16,20,21,32–35], while larger particles are potentially reactive in concrete [36–38].

Besides the ASR risk, other properties of concrete can also be influenced by glass particles. The specific density of glass is lower than that of conventional aggregates, resulting in a decreased density of concrete. Workability and mechanical properties of concrete are also influenced [21,32,33,38–44]. The smooth texture of glass aggregates changes the workability (lower water demand) and reduces the strength of concrete, as the adhesion and interlocking effects between the cement matrix and glass aggregates are weaker than for conventional aggregates. It has been found that a replacement of up to 20% of conventional aggregates with glass does not significantly change the strength of concrete [41–43], whereas for replacement levels higher than 30% the reduction becomes more significant.

The photocatalytic oxidation (PCO) technology is increasingly often applied in building materials to provide them with self-cleaning and/or air-purifying properties. The most commonly used photocatalyst – TiO_2, is proven to perform well in concrete exposed to the outdoor environment. Recently, a full scale demonstration project in Hengelo, the Netherlands, has shown that a significant air pollutants removal (e.g. NO and NO_2, denoted later as NO_x) in the urban environment can be achieved by photocatalytically active concrete [45]. The reported results show that an average NO_x concentration reduction reached over 19% during the entire day length and up to 28% when considering only the afternoons, when the UV-light intensity is the highest. Under the ideal weather conditions the NO_x concentration could be reduced up to 45% compared to the control street paved with standard concrete stones. Besides the UV-active TiO_2 used in outdoor applications, new types of modified TiO_2 (e.g. by doping) that can be activated by the visible light are also becoming widely available. Thus, this type of photocatalyst can be used also in indoor applications. Nevertheless, as TiO_2 is still considered as a relatively expensive additive compared to traditional building materials such as concrete, it is desired to apply it in an optimal and efficient way. As demonstrated in [46,47], one way to minimize the amount of TiO_2 photocatalyst addition in concrete and improve its air purification ability is by a combined application of TiO_2 and glass aggregates. The light transmittance and reflection properties of glass particles are considered the main factors for the PCO efficiency enhancement, as the transferred light could be better scattered across the concrete matrix and activate the TiO_2 particles more efficiently. Therefore, a higher concrete surface at which the PCO oxidation takes place could also play an active role in the process [47].

Combining the sustainability of the application of waste glass together with the aesthetic and functional properties, the aim of the present study is to develop a functional waste glass-based, durable and strong concrete with unique properties: translucency and enhanced air cleaning properties. This is achieved by utilizing waste glass in different size fractions and TiO_2 photocatalyst to produce concrete tiles of various thicknesses. As the currently available literature investigates mainly the application of washed glass in concrete, this article targets also on concrete prepared with unwashed waste glass.

2. Materials

The waste glass used in this study originates from a glass recycling company (Maltha Glasrecycling Nederland B.V.) and has particles in the size range of 20 μm up to 14 mm. In total, five different glass fractions are used, as illustrated in Fig. 1. The received glass is considered a waste material due to its high chemical pollution and contamination that are too high for recycling in glass production factories. Prior to the delivery, it has been screened to different size fractions and stockpiled in natural weather conditions. In this study, the fine and coarse waste glass aggregates are firstly applied in concrete in their original, polluted form. This pollution mainly includes decomposed organics (sugar, fat, etc.) and soil. Due to the detrimental influence of the pollution on concrete properties,