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Structurally and environmentally favorable masonry units for infilled frames

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ABSTRACT

Infill in frames can have detrimental or beneficial effects, and among parameters that influence interaction, infill type stands out as a common element. Masonry units utilized for masonry structures are also frequently utilized as a frame infill. Consequently, their higher strength and stiffness greatly influence the surrounding frame, which can often lead to undesired effects. Therefore, a different approach is proposed – designing a masonry unit with structurally favorable properties for an infill. Lower stiffness and strength of infill can generally benefit the structure as in comparison to a bare frame such infill provides stiffness, but has a higher potential to sustain enough damage to prevent significant detrimental effects on the frame. Out of plane stability, compactness and lightweight are favorable, which is necessary to combine with environmental aspects. To encompass favorable goals, a new masonry unit was developed, based on research of 13 self-compacting concrete mixtures with recycled materials in their composition. Utilizing recycled crushed brick and ground expanded polystyrene enabled reductions in weight, carbon footprint, stiffness and strength. Among various mixtures, based on key material properties, two were selected for production and further testing of masonry units. Units' density, stiffness and strength showed potential for application as non-structural infill. With a mortar mixture that showed favorable and reliable experimental results, masonry wallets were tested for compression strength and modulus of elasticity, which confirmed developed units potential. From available literature collected results of modulus of elasticity and compressive strength on masonry wallets indicate that developed units are very similar to AAC units, but with significant environmental advantages. Designed mixtures of self-compacting concrete with developed unit shape show great potential for use as non-structural infill, with highlighted positive interaction aspects of a frame-infill composite. This enables the engineer to take a more active role in design, by preventing detrimental effects through choice of constituents in a frame-infill composite.

1. Introduction

Infilled frames, whether steel or reinforced concrete (RC) ones, were and still are a focus in a large number of experimental and numerical investigations. Such research efforts are primarily rooted in lack of guidelines for their design in modern normative documents, especially in regards to earthquake, i.e. horizontal loading [1]. Although this composite system can be beneficial, and as such, the influence of infill can be conservatively omitted, that is not always the case [2–4]. This warrants twofold attention, one for the sake of rationality and savings in design when infills effect is beneficial, and one for reliability issues in design when the effect is detrimental. It is important to note that detrimental effects include premature failure of the system due to limited displacement capacity, and thus possible loss of human lives. The subject of adequate design procedures is complex as a large number of variables governs the response of such a system to horizontal loading. Initial stiffness, load capacity and drift capacity are all greatly influenced by the interaction of infill and frame in relation to a bare frame [5].

Some of the most important parameters that affect interaction are type of infill, type of frame, type of connection between constituents, ratios of stiffness and strengths between constituents and individual members of constituents [5,6]. With that in mind, a thought out influence on these variables can greatly effect behavior of an infilled frame system, of which infill as a common element for both RC and steel frames stands out. It is common practice to use structural types of masonry units as frame infill. These kinds of masonry units consequently have higher strength so the interaction with the surrounded frame is more pronounced and can lead to undesired effects.

However, infill with a lower stiffness and strength can generally also benefit the structure as it offers the possibility to provide more stiffness in the elastic domain, with a higher strength, in comparison with a bare frame. In addition, with its lower strength infill can sustain enough damage to prevent significant detrimental impact on drift capacity. This

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is connected to two fundamental approaches of design of infilled frames: masonry infill is regarded as a valuable structural part of the system trying to maximize its contribution; masonry infill is a 'necessary' functional part of the structure and its influence should be carefully monitored. Namely, displacement capacity and interstory drift are directly correlated to damage and collapse. Compact infill units are preferred as they provide better reliability and consistency in behavior, due to their better in and out of plane stability [7], but this is often in contrast to the requirement of lower strength as their surface areas are larger. In this context, the term compact is used to describe a unit that has higher ductility, which can be associated with the ratio of holes volume to the gross volume, and the material used, regarding its behavior. Additionally, out of plane stability is important as it prevents damage to surrounding areas and enables easier function repair [8]. In terms of erection simplicity, cost, and dead load (and in turn inertial load) reduction, infill is preferred to be as lightweight as possible. Environmentally, infill represents the majority of vertical elements area in a floor layout, which in fact correlates to the carbon footprint of a building. This is multiplied when infill is considered as a sacrificial element in an earthquake situation, which entails that its use can potentially have more lifecycles in a single building. It is thus important to make its productions as low carbon intensive as possible, but also try to enable its reuse and inclusion in a new product lifecycle.

With given objectives from different perspectives in mind, it is needed to design a new infill unit, one that would to the largest extent encompass them all. Once again, it is important to note that masonry units used as infill do not need to be a part of the structural system, as they do in masonry structures. Clay masonry units do not provide adequate possibilities of lowering their environmental influence, primarily in the carbon intensive production stage. Additionally, they have a higher embodied energy and carbon count than concrete to start with [9]. From a structural standpoint, in a compact form, clay units have high strength, which is difficult to grade, combined with high stiffness, which is also undesirable for infill. Concrete enables gradation of strength and consequently stiffness, recycled materials can be incorporated in its production, and it can be reused as a secondary crushed material. These options make concrete a viable choice in pursuing set structural and environmental objectives.

Of several types of concrete, self-compacting concrete (SCC) can be viewed as the most favorable for successful masonry unit production, with set objectives in mind. This is primarily due to the same possibility of manipulation in composition as with regular concrete, with added benefits that are in accordance with desired environmental and ease of fabrication effects. These benefits include [10] increase in durability, no need for vibration and thus easier masonry unit mold filling with a better quality finish, and no aggregate segregation.

Partial or complete replacement of natural aggregate with secondary materials not only reduces the carbon footprint, but also reduces strain on already overflowing waste disposal sites. With that in mind, clay brick waste is especially interesting. It is abundant as a demolition and manufacturing by-product (waste) material, which makes it environmentally and financially effective. There are clear advantages from a structural point of view also. Namely, the desired effects of strength and stiffness reduction can be achieved by replacing natural aggregate with recycled crushed brick (RB) material in larger percentages. This was confirmed by Cachim [11] with RB aggregate replacement of up to 30%, and by Debieb and Kenai [12] for coarse and fine RB aggregate with higher percentages of replacement. Specifically for SCC, Singh, Kaushik [13] found that brick dust and marble powder could be effectively used for satisfactory slump and setting times. Additional improvements of desired effects can be achieved by implementing polystyrene foam in SCC composition. This results in a more lightweight concrete and in additional reductions of strength and stiffness, which is confirmed by Mandlik, Sood [14]. Environmentally, polystyrene is widely used as a packaging material after which it is usually disposed. Since polystyrene is not biodegradable, its implementation in a new product is desirable. In addition, polystyrene forms airspaces, which should be beneficial for infill thermal properties and further carbon footprint reduction of the building as a whole during use.

It is obvious that there are significant indicators, from structural and environmental standpoints, that justify research and development of a SCC based masonry unit for utilization as infill in RC and steel frames. The purpose of this research is consequently to design and investigate relevant properties of an SCC mixture utilizing crushed brick and polystyrene aggregate. This is to be followed by a selection of possible mixtures, based on provided parameters, for masonry unit production. With further investigations of relevant properties on produced masonry units, an additional objective is to determine properties on a masonry level, which are fundamental for possible frame-infill applications.

2. Properties of concrete

The first design step for a new masonry unit is to develop SCC mixtures, utilizing water, two types of binder, and different types of aggregates and fillers. Natural aggregate was fully replaced with recycled crushed clay bricks (RB), obtained as an industrial waste product or with a combination of RB and ground expanded polystyrene (GEP), obtained by mechanical recycling of expanded polystyrene (EP). RB was saturated surface dry before the mixing procedure, with regard to the water absorption percentage of each fraction of RB. Aggregate grading curves are shown in Fig. 1.

In total 13 mixtures were designed and made, varying by binder type and ratios of constituents in composition (Table 1). Portland composite cement CEM II/B-M(V-L) 32.5 N [15] and building calcium lime CL 90-S [16] were used as binders, and brick dust (BP) and dolomite powder were used as fillers. Concrete compositions were designed in accordance with recommendations of The European Guidelines for Self-Compacting Concrete [17], with an objective to achieve low strength SCC, as defined by ACI [18]: controlled low-strength material (CLSM) usually has a compressive strength of 8.3 N/mm^2 or less. Additives in the form of viscosity modifying admixture (VMA) and superplasticizer (SP) were used in all mixtures, and air-entraining admixture (AEA) in mixtures SCC-20 to SCC-40c. Air-entraining admixture was used as EP beads make concrete prone to segregation during casting, which results in poor workability and lower strength.

The impacts of RB on key fresh properties such as filling ability and passing ability of SCC, as well as properties in its hardened state, were experimentally investigated to determine positive indicators for use as concrete masonry units. Properties of lightweight SCC in the fresh state, such as density, air content, flow ability, flow rate, and passing ability were tested in accordance with EN 12,350 [19–22] (Table 2). Density of SCC with RB as an aggregate is higher than that of mixtures with the addition of GEP, and air content is inversely proportional (combination of RB and GEP entrains more air during mixing). The T_{500} time test determined that mixtures SCC-3, SCC-4, and SCC-5 to SCCS-40c are

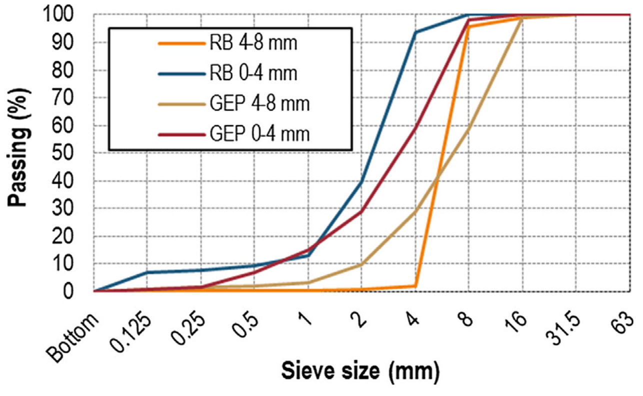

Fig. 1. Grading curves for RB and SF.