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Optimisation of rubberised concrete with high rubber content: An experimental investigation

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HIGHLIGHTS

- Fresh & hardened properties of rubberised concrete (RuC) are studied experimentally.
- Various tyre rubber types & contents are used to replace fine/coarse aggregates.
- A mix optimisation improves the RuC strength by up to 160% at 100% sand replacement.
- Use of Silica Fume and PFA improves packing and increases RuC strength by up to 44%.
- Optimised RuC with high rubber content is deemed suitable for use in construction.

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ABSTRACT

This article investigates experimentally the behaviour of rubberised concrete (RuC) with high rubber content so as to fully utilise the mechanical properties of vulcanised rubber. The fresh properties and short-term uniaxial compressive strength of 40 rubberised concrete mixes were assessed. The parameters examined included the volume (0–100%) and type of mineral aggregate replacement (fine or coarse), water or admixture contents, type of binder, rubber particle properties, and rubber surface pre-treatments. Microstructural analysis using a Scanning Electron Microscope (SEM) was used to investigate bond between rubber and concrete at the Interface Transition Zone (ITZ). This initial study led to the development of an "optimum" RuC mix, comprising mix parameters leading to the highest workability and strength at all rubber contents. Compared to a non-optimised concrete with 100% replacement of fine aggregates with rubber, the compressive strength of concrete with optimised binder material and moderate water/binder ratio was enhanced by up to 160% and the workability was improved significantly. The optimisation proposed in this study will lead to workable high rubber content RuC suitable for sustainable high-value applications.

1. Introduction

Worldwide tyre production is approximately 1.5 billion units/year and it is estimated that, for every tyre placed in the market, another tyre reaches its service life and becomes waste [1]. Over 300 million tyres reach their service life every year in the EU alone, i.e. practically one waste tyre per person. Tyres used in the automotive industry are made with 70–80% highly durable vulcanised rubber, which cannot be easily recycled. The inadequate disposal of rubber from scrap tyres is hazardous to the environment and human health and, as a result, stringent environmental legislations have been introduced to manage such "waste". The EU directives prohibit the disposal of scrap tyres in landfills and favour the reuse of waste materials ahead of recycling to minimise energy consumption (Landfill Directive 1991/31/EC [2] and Directive 2008/98/EC [3], respectively). This has increased efforts towards generating new applications for vulcanised rubber from scrap tyres [4–12]. In the past two decades, numerous studies have investigated the reuse of recovered tyre rubber in concrete to replace fractions of its mineral aggregates [5–12]. Whilst rubber is a valuable material with high strength, durability and elasticity, it can have a detrimental effect on some of the fresh and hardened mechanical properties of concrete.

In general, previous literature on the characteristics of RuC mixes is contradictory, highlighting the difficulty of achieving suitable mixes for construction. Whilst some researchers have reported satisfactory workability at all rubber contents and sizes

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[13,14], others have measured zero slump at 50% [15] or 80% [16] aggregate replacement by volume. Previous experimental work often measures concrete workability through slump [17,18]. Workability, however, is defined by the ease of mixing, placing and consolidating fresh concrete whilst maintaining adequate concrete homogeneity [19], and therefore, the overall stability (i.e. segregation and bleeding) of the fresh RuC mix has to be taken into account. Due to the relatively low density of rubber compared to mineral aggregates and cement, RuC cylinders with inadequate mix proportioning, consolidation or handling can exhibit a high concentration of rubber at the top upon vibration [20,21]. The increase in porosity and entrapped air content (up to 30% at 25% rubber replacement by volume [20]) is conceivably the main reason behind the poor fresh performance of RuC [22]. Such increase may be attributed to rubber hydrophobicity, irregular shape, rough texture, contamination, interlock among rubber particles and excessive friction with cement paste [23,24]. Other factors include flocculation among fine rubber particles, particle gradation and moisture content [22].

The compressive strength of RuC reduces by up to 90% at high levels of rubber replacement (e.g. 100% sand replacement) [25]. The lower compressive strength of RuC can be attributed to the relatively high Poisson's ratio of rubber particles (nearly 0.5), the high porosity of the composite and the weak rubber-cement paste bond (or Interfacial Transition Zone, ITZ) [26,27]. Other factors that reduce RuC strength include segregation, lower overall stiffness of the composite and casting and consolidation techniques [28]. Whilst such reduction is well documented in the literature [14,17,24,25,29–31], strength seems to be influenced by rubber content, size and properties, as well as mix parameters and proportions (i.e. water to binder ratio (w/b), type of chemical admixture and binder material). As a consequence, results from compressive strength tests on RuC cylinders are difficult to compare due to their large scatter (Fig. 1).

Whilst rubber hydrophobicity and surface texture are known to weaken the bond between rubber and cement paste, the level of bond and load transfer at the rubber-cement paste interface is still unknown. Microstructural analysis of RuC revealed higher porosity in the matrix at the rubber-cement paste ITZ, as well as a larger ITZ, when compared to conventional concrete [37,38]. In fact, the ITZ between rubber aggregates and cement paste increased from 6.65 μm to 13.44 μm at 10% and 50% sand volume replacement, respectively [38]. However, w/b was often varied with rubber content [38], which could possibly affect the hydration kinetics, mix porosity and ITZ density and width. Scanning Electron Microscopy (SEM) images have shown a lack of bonding (gap) between the rubber and cement paste at their ITZ, as well as limited hydration products surrounding the rubber particles [37–39]. Conversely, other studies show that rubber bonds well to the cement matrix

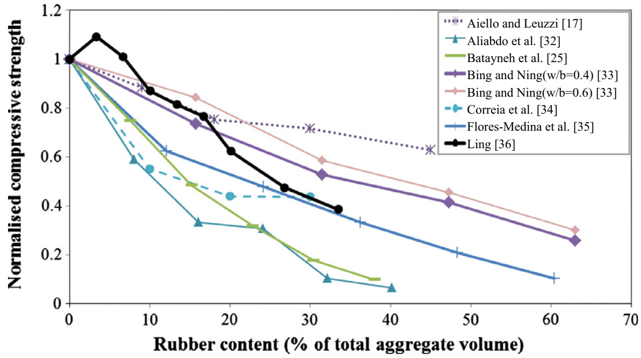

Fig. 1. Normalised concrete compressive strength versus rubber content (data from [17,25,32–36]).

[30,40]. This good rubber-cement paste bond has been attributed to interlock at the rough surface of rubber particles [40].

It has been reported that zinc stearate (used to extend tyre service life in many developing countries) increases rubber hydrophobicity and leads to a porous and weak rubber-cement interface [41]. To improve rubber-cement paste chemical/physical bonding [18], several rubber pre-treatments have been investigated such as washing with water [21,35,42], polyvinyl alcohol [43], NaOH [13,41,44,45], $Ca(OH)_2$ [46], silane coupling agents [47], organic sulphur compounds [48] or acid [40], as well as partial oxidation of the rubber surface [49], exposure to UV radiations [50] or pre-coating with cement [51], mortar [26], silica fume [39], limestone [52] or sand [45]. Despite some success in rubber pre-treatments (strength increase in the range of 3–40% [18,26,41,51,52]), results are often scattered and inconclusive, particularly when mixes with pre-treated rubber are not compared to mixes with as-received rubber [35,42]. The effects of the pre-treatments on the concrete hydration reaction and long term durability have not been investigated. The pre-treatments are also often costly and time-consuming, and can only be justified if concrete performance is enhanced.

The significance of achieving an "ideal" packing of the concrete constituents on its rheology, durability and mechanical properties has been highlighted in the literature [53]. The packing of granular particles is influenced by their shape, texture, specific gravity, moisture condition and mixing, placing and consolidation techniques. To date, an appropriate method for characterising rubber particle properties does not exist, possibly due to the different types of rubber, levels of contamination and the lack of standard tests. For instance, the specific density of rubber reported in the literature varies between 0.5 and 1.3 [7,28,54]. The reported water absorption values vary between "negligible" [27,55] up to 42.1% [33]. Nevertheless, rubber particles are broadly characterised with a flaky and elongated shape, a rough surface (i.e. high friction coefficient) and hydrophobicity that is likely to affect its packing with conventional aggregates [21,56]. Due to their high surface area to weight ratios, it is also likely that ultra-fine rubber particles interact by surface and inter-particular forces [57]. To limit the influence of rubber size on concrete particle packing, mineral aggregates are often replaced with rubber particles of similar grading [58].

Based on the previous discussion, it is evident that the lack of consensus in the literature, insufficient understanding of RuC performance and adverse effects of rubber on concrete properties limit the development/use of rubber in structural concrete applications. To date, the use of RuC has been mainly limited to:

1) Non-structural applications such as road barriers [7], thin overlays [8], concrete panels [9], paving blocks [29,31] and applications for thermal and acoustic insulation [5,6], and
2) Low-medium compressive strength structural concrete with reduced weight and increased ductility, as well as resistance to vibrations, impact and cyclic loads [6,10–12].

To minimise the negative impact of rubber on concrete strength, the use of small volumes of rubber (up to 25% of the total mineral aggregates) is often proposed [16,59,60]. This inhibits the benefits that high-quality rubber can have on the concrete toughness and ductility [61,62]. The use of large amounts of rubber in concrete can also have a positive environmental impact by reusing materials that would otherwise be considered waste. Therefore, from a structural and environmental perspective, further research is needed to mitigate the negative impact of large amounts of rubber on concrete characteristics.

This article investigates experimentally the behaviour of RuC with high rubber content so as to fully utilise the