Utilizing waste cast stone: Compression strength analysis and implication for suitable cast stone production

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Abstract. In recent years, the concept of circular economy has become increasingly popular as a sustainable approach to resource management. The present study explores the potential of reusing cast stone waste generated during the production process, in alignment with the principles of the circular economy. Cast stone waste typically goes to landfill sites discarded as a byproduct and poses environmental challenges due to its non-biodegradable nature. This work focuses on reusing this waste material as a viable resource, thus mitigating the environmental impact. Through a series of compression test experiments on cast stone, the presented study investigates the effectiveness of incorporating cast stone waste into production. The findings of this study contribute to cost reduction in raw material and waste minimization promoting economic and environmental benefits.

Keywords: Uniaxial compression test, Recycled aggregates, Cast stone

1 Introduction

Climate change and global warming are one of the major challenges being faced by this generation, which is largely driven by human activities such as industrial processes and construction. The construction industry is a significant contributor towards greenhouse gas emissions and environmental degradation due to the severe use of natural resources and production waste. As per the United Nations Environment Programme's report, the construction industry was responsible for 37% of global Greenhouse gas emissions in 2023 [1]. Raw material extraction such as aggregate mining causes damage to the riverbeds and mountains [2]. Aggregates are widely used in the cast stone production process. Cast stone is a popular construction material for architectural applications due to its ability to replicate the effect of naturally carved stone. It is also a highly durable material . The production and disposal of cast stone also result in a substantial amount of carbon dioxide emissions and contribute to landfill waste [3]. In recent years, there has been an increasing interest in sustainable construction practices that can mitigate these environmental impacts. One promising approach used in the

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industry is recycling of Construction & Demolition Waste (C&DW) as aggregates in production, hence reducing the amount of landfill waste [4]. Similarly, the waste cast stone can be used into in the production process. This approach not only reduces the need of virgin material but also minimizes the waste, hence aligning with the circular economy principles [5]. Within the construction industry, Portland cement is currently the first contributor to CO_2 emissions, hence the concrete industry is seeking to use more methods to reduce their emissions. The construction industry recently started using more environmentally friendly cementitious materials from other industries such as Ground Granulated Blast-furnace Slag (GGBS), Silica Fumes (SF) and Fly Ash (FA) in alignment with the BS EN 197-1 standard [6]. Currently, the CO_2 emissions from standardized concrete production in the UK are estimated at 76.3 kg CO_2 per tonne, which is a 26% reduction compared to 103.1 kg CO_2 per tonne agreed in the Kyoto Protocols and Climate Change Act [7]. However, these figures do not specify the strength class of concrete. For cast stone, the problem remains the same, Portland cement remains the main contributor to CO_2 emissions [3]. The cast stone industry is also moving towards greener alternatives to Portland cement; In a study by Mudgal et al., alternatives to Portland cement for cast stone have been identified for cast stone [8].

Another method to curtail relevant CO_2 emissions is by reducing the use of virgin raw materials, hence why the UK government as well as Denmark and Sweden has introduced an Aggregate Levy to prevent the use of natural resources and encourage the use of recycled material [9]. Therefore, the use of Recycled Aggregates (RA) in concrete is of significant interest because it promotes sustainable development and reduces the demand of mineral extraction reducing the amount of waste being sent to landfill. Currently, RA is used in lower-grade applications to conform with BS EN 12620 [10]. However, it can also be used for higher-grade construction applications if it conforms with BS 8500-1:2023 [11]. To promote a circular economy concrete industry has been utilizing its own waste as aggregate by using Recycled Concrete Aggregates (RCA) [12]. Most of the RCA are derived from C&DW. Compared to Natural Aggregates (NA), RCA has notable financial and environmental advantages[13]. In recent years, a vast majority of literature has focused on using RCA. In several works, it has been mentioned that Natural Aggregate Concrete (NAC) has superior compressive strength in comparison to concrete made from RCA [14-16]. In contrast to NA, RCA's surface is covered with aged mortar which leads to higher water absorption and porosity [14]. Higher water absorption leads to higher porosity in the concrete, hence reducing the strength of the concrete. The lower strength of concrete produced from RA has also been pointed to the parent concrete being weak [17]. However, some studies suggested that using a combination of recycled aggregates and admixtures (chemicals to enhance the properties of the concrete) will improve the mechanical properties of the concrete produced from the recycled aggregates [18, 19]. In a few studies, authors have argued that lower-strength parent concrete leads to higher-quality RCA as the low-strength mortar attached to the aggregates can be easily separated due to weaker bonds, creating stronger concrete [17]. Other studies suggest that concrete produced from a high-strength concrete parent RA would lead to better quality concrete as the bond between the mortar and the aggregate would be denser and stronger [20, 21].

In the concrete industry which closely resembles the cast stone industry, when the coarse Natural Aggregates (NA) have been replaced by 30% coarse RA or replaced by 20% fine RA, a marginal effect has been seen on the compressive strength of the concrete [22]. However, the strength starts to decrease gradually as more of the NA is replaced by the RA [23, 24]. It has been observed that the strength of concrete produced from either 100% coarse RA or 50% fine RA is typically 20% to 30% lower than from using NA [25, 26]. Where 100% of fine RA is used, a reduction in strength of up to 35% has been observed [27, 28]. Overall, more RA in the mix produces lower-strength concrete.

There are a lot of studies that have captured the effect on the strength of the concrete when using RA but no literature is currently available where cast stone waste has been re-introduced into the mix as RA and tested for compressive strength. To address the gap, this study aims to investigate the feasibility of using cast stone waste back as RA within the mix. It also investigates the effect of weight on compressive strength. Currently, there are three types of cast stones, Fibre Reinforced (contains Fibreglass) (FR), Semi-dry and Wet Cast (contains aggregates) (WC). For this study, only FR and WC can be considered as Semi-dry a powdery material. As per the UK Cast Stone Association, the acceptable cube strength for all cast stone should range between 35-50 MPa which also complies with BS EN 1992 and BS EN 1996 [29, 30].

2 Experiment

A few challenges faced by the CS industry is constant supply of NA. The RA used in this study comes from manufacturing waste such as rejected cast stone and spillovers. The waste from each cast stone was utilised to make the specimen for the same type. The test cubes made from the coarse RA were tested on the 14-day strength as they gained 90% of the strength during this curing period [31].

2.1 Aggregate preparation

The aggregate preparation process involved the use of WC and FR production rejection waste. The cast stone waste was initially processed using a small crusher to break it down into different-sized aggregates. Following the crushing, aggregates were separated using sieved to achieve two different size ranges of 0-2 mm and 4-10 mm. This separation ensured that the aggregates met the specific size requirements for the mix design. During the sieving process, the crushed material was passed through a series of sieves resulting in the precise sorting of the particles [10]. This methodological preparation of aggregates is important for ensuring consistency and quality in the final specimen. The parent cast stone from which these aggregates were produced the batch had a strength of 40 MPa for WC and 42.5 MPa for FR cast stone.

2.2 Test cube preparation

The original mix design was used for both WC and FR. The mix design for these recipes is commercially sensitive, so it cannot be described this study. The mix design consists of ingredients such as sand, limestone and white Portland cement blended with admixtures. Once the mix was prepared it was poured into lubricated 150 mm x 100 mm x 150 mm moulds [32]. Within the mix composition for both cast stone materials, the NA was replaced with RA by 0%, 10%, 20%, 40%, 50% and 100%. In total, 3 cubes were created for each composition equating to 21 sample in total per material. Wet cast test cubes are shown below in the mould for 0%, 10% and 10% recycled aggregates. The test cubes were left overnight within the moulds to cure, this initial setting process was completed under controlled conditions. The next, day the cubes were carefully demoulded and weighed to record initial mass. The cubes were then submerged in a water tank to undergo further curing, which is initial for the hydration process that contributes towards the strength development of the cast stone. The test cubes remained within the water tank to gain 14-day strength, which is critical for cast stone to achieve 90 % optimal performance and provide reliable data for subsequent testing [31]. Before the test, the wet weight of the cubes was noted to highlight any change in the density of the cubes.

3 Result

3.1 Wet cast

The compression test was performed in compliance with BS EN 12390-3 [33]. The WC cubes were subjected to the compression test on the 14th day. As shown in Figure 1, the cube samples S1, S2 and S3 with 0% recycled aggregates had the highest strength overall. Sample S3 had the highest strength, of 54.1 MPa. When 100% of coarse NA is replaced with the coarse RA, the strength is lowest between 33.6 MPa to 35 MPa. On average, the highest compression strength can be seen between 20% and 40% replacement of 12%.

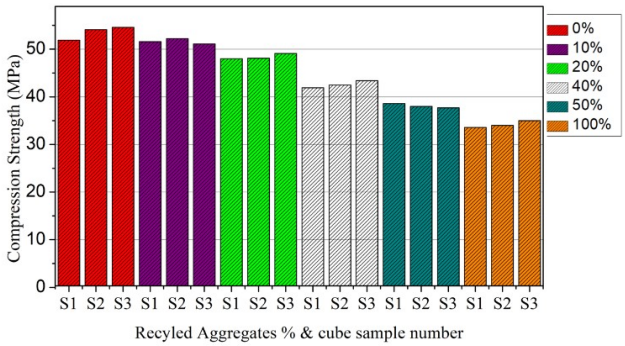


Fig. 1. Bar chart between Wet cast compression strength and % recycled aggregate replacement per sample

The correlation between the weight and compression strength can be seen in Figure 2. Cube samples with the lowest weight have the lowest strength and the heavier cubes have more strength. For instance, cube samples S1 with 100% RA have the lowest compressive strength compared to 0% RA samples. At 40% RA, the samples weighed the same, however, all three samples have different compressive strengths of 32.2 MPa, 34.4 MPa and 33.7 MPa for S1, S2 and S2 respectively.

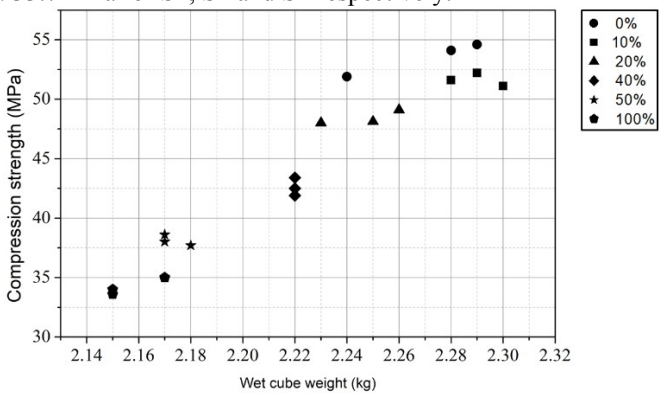


Fig. 2. Compression strength Vs wet cube weight (kg) for Wet cast

3.2 Fibre-reinforced

Similar to Wet cast, a reduction in strength is observed as shown in Figure 3. Sample S3 with 0% recycled aggregates has shown the highest strength whereas in sample S2 with 100% recycled aggregates, the lowest strength is observed. It can also be observed in Figure two that the cube strength on average drops drastically as soon as RA is introduced to the mix. On average, the reduction in the strength is 26% between 0% RA to 10% RA.

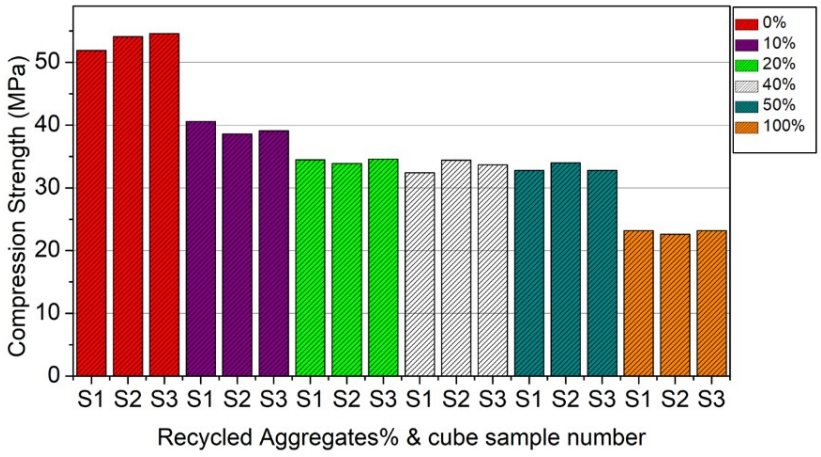


Fig. 3. Fibre compression strength Vs % recycled aggregate replacement per sample

A similar behavior to WC can be observed in the weight vs compressive strength chart. The lightweight sample with 100% RA had the lowest strength as shown in Figure 4. Cubes with no recycled aggregates achieved the highest 14-day strength.

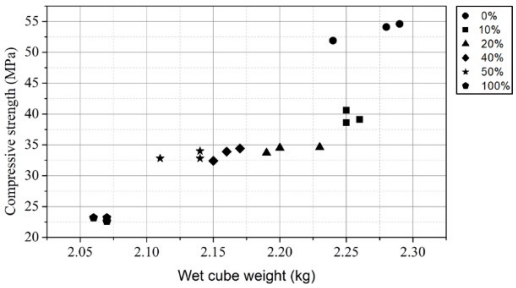


Fig. 4. Compression strength Vs wet cube weight (kg) for fibre-reinforced

4 Discussion

The results from sections 3.1 and 3.2 indicate that the cubes with higher 100% recycled aggregates exhibited the lowest compressive strength for both WC and FR cast stone. This reduction in strength can be attributed to the inherent weakness in recycled aggregates which often have pre-existing microcracks and a higher porosity compared to the NA. The weight and strength measurements further corroborate these findings with cubes with higher RA being lighter, suggesting higher void content. The presence of voids within the cast stone will reduce the density of the overall density and adversely affect the quality of the cast stone. Additionally, the fibre reinforcement was not able to bridge the gaps effectively. However, in both cases, the replacement of aggregates is still under the acceptable compressive strength limit of UK cast stone standards. In WC, from 0% to 50% RA is under the acceptable compressive strength. Similarly, in FR, 10% RA is under the acceptable limit.

5 Conclusion

To promote the circular economy and reduce overall greenhouse gas emissions, this study investigated the compressive strength of Wet cast and Fibre-reinforced cast stone with recycled cast stone aggregates. The initial findings reveal that with the increase in recycled cast stone aggregates within the mix, lower compressive strength is achieved. However, certain compositions of both materials are still acceptable by the UK Cast Stone Association standards as they were above 35 MPa strength. It also assures that a circular economy can be achieved in the cast stone industry by using construction and demolition waste. The primary objective of this study was to evaluate the feasibility of using recycled cast stone waste as aggregates. However, for future study a design of the experiment must be performed for a thorough testing of the samples for repeatability.

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