

Assessing The Mechanical And Durability Performance Of Concrete Made Using Recycled Clay Masonry Rubble Bricks (CMRB) As Coarse Aggregates

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Abstract. The South African construction industry is currently faced with mounting construction waste and overflowing landfills. Consequently, the feasibility of using of clay masonry rubble brick (CMRB) as a partial replacement for natural coarse aggregate in concrete was investigated. Three concrete mixes were made using a water-to-binder (w/b) ratios of 0.60. A control mix as well as a mix containing 50% and 100 % replacement of coarse Andesite aggregate with CMRB as coarse aggregate was tested. The compressive strength, shrinkage and durability properties (with respect to oxygen permeability, water sorptivity and chloride conductivity) were assessed. The results show that the incorporation 100% MCR brick as coarse aggregate produced the lowest compressive strength result, the highest shrinkage rate and the least resistance to gaseous ingress and chloride conductivity. The concrete mix containing 50% MCR brick exhibited the least resistance to water absorption through capillary action. The mechanical and durability properties of both concrete mix containing MCR brick was largely affected by the porous nature of coarse masonry rubble. The results can be attributed to a relatively high void ratio leading to the presence of more interlinked pathways within the CMRB aggregate.

1. Introduction

In developing countries the growing population has driven an increase in the demand for commercial and housing infrastructure. In addition there is an increase in the number of demolished and/or abandoned houses potentially resulting in tonnes of construction and demolition (C&D) waste being generated annually. Owing to the lack of guidelines on the re-use of C&D waste in South Africa, the waste gets sent to landfill sites or is illegally dumped, subsequently exacerbating the negative impacts that the built environment has on the natural environment[1].

In a bid to create a more sustainable construction industry, circular economy has placed emphasized on the need to mitigate these negative impacts on the environment. This has led to an accompanying rise in research that looks to reuse such waste material. Waste material is exploited in a manner that both reduces cost and cleans the environment [2].

One way in which to incorporate C&D waste material in future construction projects is to use it as aggregates in mortar [2] and/or concrete. Aggregates constitute 60 to 80% of the volume of concrete, supplementing or completely replacing the natural material already in use with reused and recycled synthetic or waste material would reduce the demand for natural aggregates [3-6].

Sustainability is the desired goal within most disciplines including the construction industry and many researchers are finding new ways to reach this target. Using environmentally friendly constituents to produce concrete will help reach this goal. It is important to put careful consideration in the type of aggregates used in concrete as they determine the dimensional stability and therefore strength of concrete. Their properties play a vital role in influencing the properties of concrete as they make up 75% of the mass and approximately 67% of volume of concrete, with coarse aggregates constituting a third of that volume. Changes in coarse aggregate can therefore significantly change the strength and durability of concrete.

Various waste materials have been researched as viable replacements of natural andesite aggregates. These include, but are not limited to, rubber obtained from the waste produced by rubber-tyre industry [7 & 8] recycled plastic i.e. high-density polyethylene sourced from municipal waste [9], glass to produce a composite referred to as glascrete [10] and masonry rubble [3].

This study forms part of a larger project in which the feasibility of using clay masonry rubble bricks as aggregates in concrete was investigated. Clay masonry rubble bricks were selected in particular owing to the vast quantity of the material that has been discarded.

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This paper focuses on the viability of replacing coarse aggregates with masonry rubble from demolished buildings and its effects on the mechanical properties of fresh and hardened concrete. The properties that are investigated include workability, compressive strength, drying shrinkage, and durability. Due to a restricted study timeframe, properties that require a longer testing duration (more than 3 months) such as creep were not investigated.

2. Methodology

The following section outlines the experimental approach used to assess the mechanical and durability properties of concrete made using recycled CMRB as coarse aggregates.

2.1. CMRB as coarse aggregates

2.1.1. Sourcing clay masonry rubble bricks

CMRB aggregates were derived from clay masonry bricks collected from an illegal dump site located in Johannesburg South, South Africa (Fig.1).



Fig. 1 Clay masonry rubble bricks collected at an illegal dump site in Johannesburg South.

The CMRB were subject to mechanical crushing a to produce particle size and grading characteristics that were comparable to the control 19mm coarse Andesite aggregates used in this study.

2.1.2. Mechanical crushing and grading of CMRB

Excess mortar was removed from the CMRB (using a hammer and chisel) such that approximately less than 5% of mortar was present prior to crushing the bricks. The “cleaned” rubble shown in Fig. 2 was crushed using a hammer into sizeable pieces which classified as either fine or coarse aggregates in accordance with SANS 1083 [11]. The coarse aggregates with nominal sizes between 4.75 mm and 19 mm were selected, with the inclusion of finer particles to match the particle size fractions obtained for the 19mm Andesite coarse aggregate aggregate grading profile, in accordance with SANS 201: 2008[12].

The grading profile as seen in Fig 3, was used to determine the amount of masonry rubble aggregate required to produce a grading profile comparable (in terms of fraction size and mass,) to that produced using natural 19mm Andesite coarse aggregate (as described in SANS 1083).



Fig. 2: “Cleaned” clay masonry bricks crushed into smaller aggregate fractions.

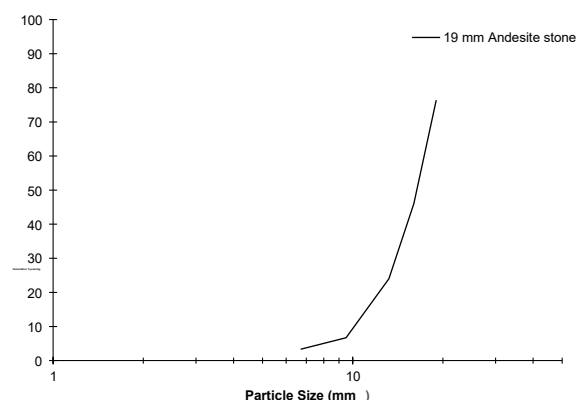


Fig. 3: Grading profile for 19 mm Andesite stone

2.2. Concrete mix design

Three concrete mixes with 0, 50 and 100% replacement of the coarse CMRB aggregate were then designed with a w/b ratio of 0.6. The details of these mix designs are summarized in the Table 1.

Table 1: Concrete proportions in kg/m³

Constituents	0% CMRB	50% CMRB	100% CMRB
PC (CEM I 52.5 R)	301	301	301
FA	129	129	129
Sand Content (Andesite)	799	799	799
Stone Content (Andesite)	1050	525	0
Stone Content (CMRB)	0	525	1050
Water	259	259	259
Admixture	0	0	0

2.2.1. Preparation of CMRB aggregates prior to casting

Prior to casting, the crushed CMRB aggregates were prepared according to a modified method adapted from De Venny [3]. Due to their high porosity (absorption), the crushed CMRB aggregates greater than 6.2 mm were first weighed, soaked in water for 30 minutes, removed from water, weighed once more, and set to dry for 1 hour prior to their inclusion in the concrete mix. The aggregates were further laid on a flat surface and covered in a layer of paper towel to absorb any excess moisture present on the surfaces of the aggregates (Fig.

4). This process ensured that the crushed masonry aggregates remained surface-dry when added into the concrete mix.



Fig. 4 Crushed CMRB soaked in water and subsequently laid out to dry.

2.3. Fresh concrete properties

2.3.1. Slump tests

To measure the workability of fresh concrete, slump tests were conducted in line with SANS 5862-1:2006 [13].

2.4. Hardened concrete properties

2.4.1. Compressive strength tests

The 100 mm concrete cubes were tested in accordance to SANS:5863[14]. The cubes were loaded using a cube press-foot machine which had a maximum loading capacity of 2 000 KN. The compressive strength tests were performed at 14 and 28 days.

2.4.2. Drying shrinkage

Drying shrinkage was conducted according to SANS 6085 [15], using 200 × 100 × 100 mm concrete prisms. Three specimens were prepared for each concrete mix.

2.5. Durability test

Three durability index (DI) tests the oxygen permeability test, water sorptivity test and chloride conductivity test were performed. These tests measure the resistance of the cover concrete to the transportation of ions and fluids through the concrete thus affecting deterioration. The tests produce reliable indices for the characterization of concretes.

The DI test specimens were prepared in accordance with SANS 3001: CO3-1[16], as seen in Fig. 5.

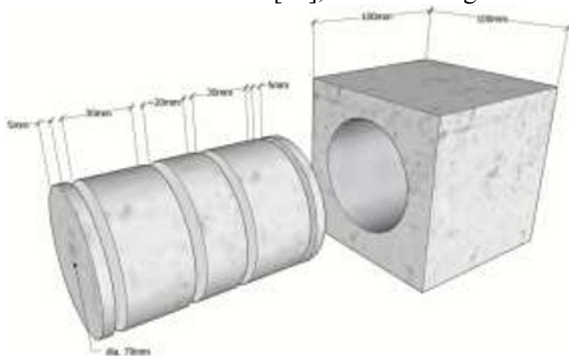


Fig. 5: DI Disc preparation from a 100 mm concrete cube [16]

The oxygen permeability index (OPI) test was conducted according to SANS:3001-CO3-2 [17]. The water sorptivity test was conducted in accordance to the Durability Index Manual [18]. The chloride conductivity test was conducted according to SANS:3001-CO3-3 [19].

3. Results and discussion

The investigation into the mechanical and durability properties of concrete made using CMBR as coarse aggregates was conducted over a period of three months. The results are outlined and further discussed below.

3.1. Fresh concrete properties

3.1.2. Slump test

The slump tests results in Fig. 6, showed a general trend, as the percentage of CMBR increased there was a decrease in the workability of the concrete.

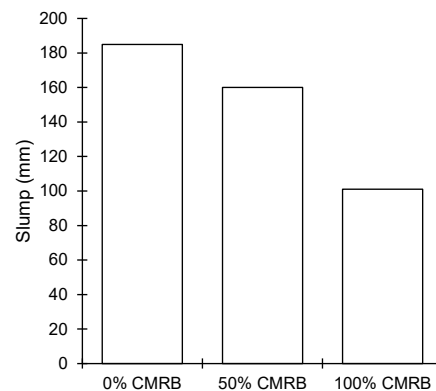


Fig. 6: Slump results for concrete made using 0, 50 and 100% CMRB as coarse aggregate

It can be seen that even after pre-soaking the CMBR aggregates for 30 minutes prior to incorporation them in concrete mixture, the high porosity rubble absorbed some of the mixing water leading to the decrease in the workability, hence a decrease in slump. Thus the higher the percentage of replacement of coarse CMRB aggregates, the less workable the concrete produced.

3.2. Hardened concrete properties

3.2.1. Compressive strength

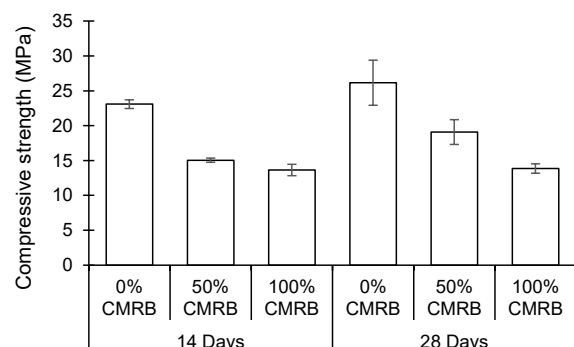


Fig. 7: Compressive strength of concrete made using 0, 50 and 100% CMRB as coarse aggregate at 14 and 28 days

In general the compressive strength is observed to decrease as the replacement percentage of CMRB aggregates increases as seen in Fig. 7, confirming work done by Khalaf [20] and Zong *et al.* [21]. This results is attributed to the high stiffness of the Andesite aggregate relative to the CMRB aggregates.

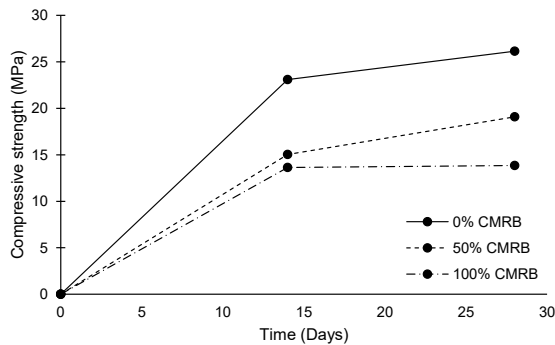


Fig. 8: Strength development of concrete made using 0, 50 and 100% CMRB as coarse aggregate

The compressive strength of 50% and 100% CMRB concretes are approximately 35 and 41 % lower than the strength of the control mix at 14 days, respectively (Fig. 8). This is a significant decrease in the compressive strength compared to the control mix which highlights the significant influence the type of aggregates has on compressive strength. A similar trend in strength gain is observed from day 14 to 28, albeit at a decreasing rate.

The differences in compressive strength results are further explained by examining the broken surfaces of the crushed concrete cubes at 28 days as shown in Fig. 9.

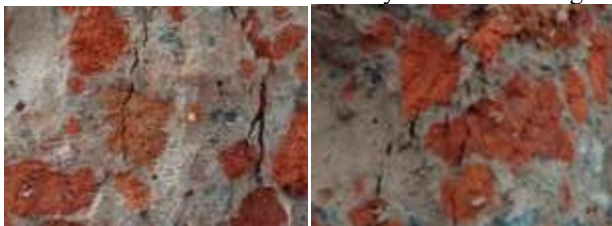


Fig. 9: Broken surfaces of concrete containing 100% CMRB

Concrete containing 0% CMRB showed a relatively high amount of the Andesite aggregates to be intact and failure had occurred along the Interfacial Transition Zone (ITZ). In contrast, concrete containing 50 and 100% CMRB showed a number of cracks running through the CMRB aggregates. This indicates that the load traversed through some of the recycled CMRB aggregates, as this was the path of less resistance, resulting in failure.

As such, this observation implies that the ITZ is stronger than a large majority of the masonry rubble aggregates but weaker than andesite aggregate in the concrete matrix. For a concrete matrix containing 0% CMRB aggregates failure is thus governed by the strength of the ITZ and hardened cement paste. In concrete with 50 and 100% CMRB aggregates, failure is mostly controlled by the strength of CMRB aggregates and the ITZ.

3.2.2. Drying shrinkage

Fig. 10 illustrates the cumulative average microstrain for concrete made using 0, 50 and 100% CMRB as coarse aggregate over a 30 day period. The 100% CMRB mix had highest cumulative strains that were 0.01% and 15% greater than those in 50% and 0% CMRB mix, respectively.

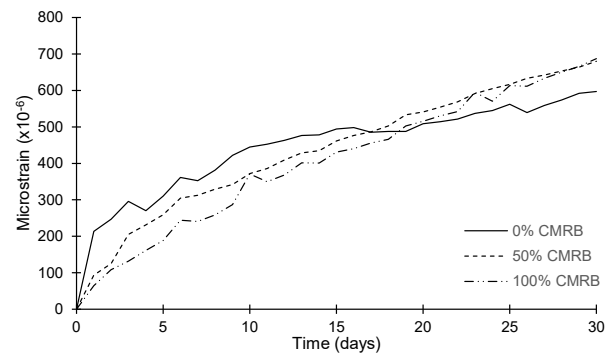


Fig. 10: Accumulative shrinkage for concrete made using 0, 50 and 100% CMRB as coarse aggregate

The accumulative shrinkage observed highlights the influence that crushed masonry aggregates have on the ability of the concrete to resist excessive volume changes due to a loss of moisture. Shrinkage of a given concrete depends on the cement paste furthermore the addition of aggregates increases the dimensional stability of a concrete [22]. From the results obtained and work done by Adam *et al.* (2001) [23] and Adamson [24], the inclusion of CMRB aggregates decreases the dimensional stability of a concrete, owing to the porosity of the aggregate. This, like in the compressive strength tests, is a result of the porous, highly absorptive and brittle nature of the crushed masonry aggregate. These aggregates are less dense due to the increased amount of voids present, within which fluids may be trapped. This therefore implies that concrete made with CMRB will lose more water in addition to that lost by the cement paste.

3.3. Durability

The durability of concrete can be measured by the oxygen permeability index, water sorptivity and chloride conductivity tests. All three durability indices were obtained to determine the overall durability of concrete incorporating coarse CMRB aggregates.

3.3.1. Oxygen Permeability Index

The Oxygen Permeability Index (OPI) is indirectly proportional to permeability. The value of OPI indicates the resistance of a given concrete to the ingress of gases. A high value of the OPI corresponds to a high resistance to gaseous ingress.

A general trend can be observed in Fig. 11, the OPI value decreases with an increase in replacement of CMRB aggregates. An increase in the amount of CMRB used therefore implies an increased susceptibility to gas movement within the concrete. This is as a result of the highly porous characteristic of masonry rubble which encourages the movement of fluids within its skeletal

structure. Such concrete is prone to carbon dioxide ingress of which may lead to carbonation induced corrosion within the concrete.

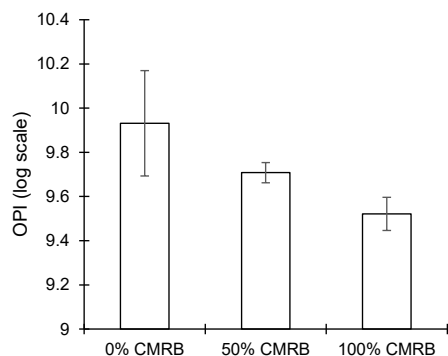


Fig. 11: OPI for concrete made using 0, 50 and 100% CMRB as coarse aggregate

3.3.2. Water sorptivity index

Ingress of moisture in concrete by capillary suction is obtained using this index. A higher value of WSI implies a decreased resistance to the ingress of liquids in a given concrete specimen.

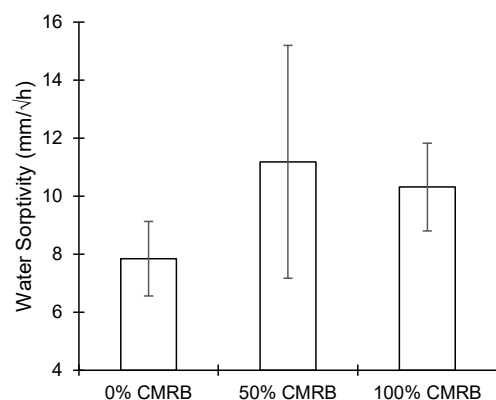


Fig. 12: Water sorptivity for concrete made using 0, 50 and 100% CMRB as coarse aggregate

It is observed in Fig. 12 that 50% CMBR mix has the highest WSI value, which seems like an anomaly as the 100 % CMBR mix would be anticipated to have the higher WSI value owing to porous nature of the CMBR aggregate.

3.3.3. Chloride conductivity index

Chloride Conductivity Index (CCI) indicates the resistance of concrete to the ingress of chloride. A higher CCI value suggests a decreased resistance to chloride ingress.

As seen in Fig.13 CCI values increases as the replacement of Andesite with CMBR aggregate increases, which verifies research presented by Adamson [24]. This is due to the highly porous property of CMBR aggregates. The resistance of 0% CMBR mix is approximately 79% and 83% greater than the resistance of 50% and 100%CMBR mix, respectively.

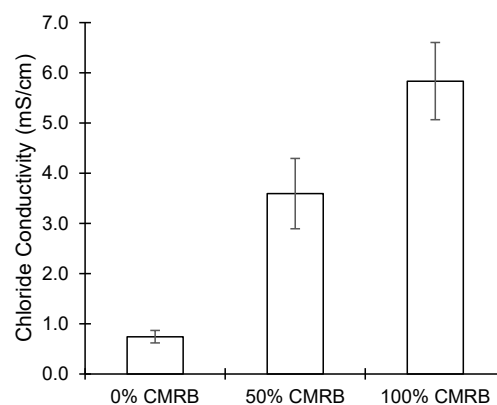


Fig. 13: Chloride conductivity for concrete made using 0, 50 and 100% CMRB as coarse aggregate

A linear relationship is also presented in Fig. 14 which indicates that an increase in porosity is directly proportional to an increase in CCI. This corresponds to the increasing percentage of replacement of Andesite with CMBR aggregate. As a result, the percentage of crushed masonry aggregate required for a given value of CCI may be determined indirectly.

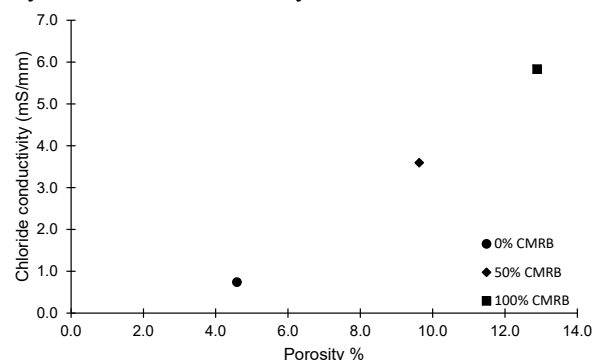


Fig. 14: CCI plotted against the corresponding porosity of concrete made using 0, 50 and 100% CMRB as coarse aggregate

This property is of particular importance in regions where the risk of chloride induced steel corrosion are high. As such, the use of CMBR increases the likelihood of chloride induced steel corrosion [25]. The higher the amount of crushed masonry rubble used, the higher the chances of steel compromise. It is therefore not recommended to use masonry rubble as aggregates in such regions.

4. Conclusion

The effects of replacing coarse Andesite aggregate with coarse CMBR aggregate on the mechanical properties of fresh and hardened concrete was assessed in this study. Three concrete mixes were investigated: 0% CMBR (the control mix), 50% CMBR and 100% CMBR. In addition, to avoid the absorption of water required for hydration, the masonry rubble aggregate was prepared further by pre-soaking and drying until surface dry conditions were reached. The properties tested include: workability, compressive strength, drying shrinkage and South African durability index of each concrete mix produced. The results are summarized below:

- The slump results obtained indicate that the higher the percentage of replacement of CMRB aggregates, the less workable the concrete mixture. Despite having pre-soaked the aggregates before mixing the concrete.
- The compressive strength decreased as the replacement percentage of CMRB aggregates increases for a given concrete mixture. This result is attributed to the highly porous nature of CMRB aggregate relative to coarse Andesite aggregate. This observation is based on the increased frequency of cracks present in concrete containing coarse CMRB aggregates compared to concrete containing coarse Andesite aggregate, thus decreasing the dimensional stability of the concrete.
- Analysis of drying shrinkage was done over a period 30 days, the results highlight that an increased amount of coarse CMRB aggregate within the concrete leads to a higher rate of shrinkage of the hardened concrete. 0% CMRB mix was observed to have the lowest accumulated strain over the 30 day period in comparison to the 50 and 100% CMRB mixes.
- For all three mixes, three durability indices were assessed. OPI results show that the higher the content of CMRB aggregate the lower the OPI value obtained. This implies that 50 and 100% CMRB mixes are more susceptible to gaseous ingress relative to 100% CMRB mix.
- The WSI tests revealed that the 50% CMRB mix had the highest WSI, thereby rendering it the least resistant to the ingress of water. Regarding 0% CMRB mix, it produced the lowest value which was as a result of the absence of CMRB within is matrix, decreasing its potential to absorb an increased amount of water.
- The CCI tests, like in OPI tests, yielded conclusive results in which the mix with highest replacement level of CMRB aggregate, had the highest CCI. Once again, this is results is attributed to the high porosity of the coarse CMRB aggregates used within the concrete.

In summary, the mechanical properties of concrete incorporating CMRB are negatively affected by the porous nature of coarse CMRB aggregates. The increased void ratio of the material implies an increased number of interlinked pathways within the aggregate which promote the transmission of stresses and strains, and encourage the movement of fluids within the concrete.

5. Further testing and Recommendations

Based on the results obtained, it is reasonable to suggest that concrete containing coarse CMRB aggregates, may be designed to meet low strength requirements. However the variability and durability of the concrete produced needs to also be taken into account. Furthermore, tensile strength tests, fire resistance tests and determinations of the elastic moduli have to be done prior to its applications.

The testing of other replacement levels below 50% may be considered to confirm work done by Zong [21] who recommended a replacement level of 30%.

Lastly, from the research presented in this study, Mix 50% is recommended for used as low strength concrete utilised in low-cost housing and/or 1 story building where foundations do not need to be excessively strong, pavement kerbs, pedestrian footpaths, strip footings for free standing walls. These buildings would have to be situated within inland regions not susceptible to excessive moisture exposure. This ensures that the embedded reinforcement does not experience chloride attacks leading chloride induced steel corrosion promoted by excessive fluid ingress.

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