YCRETS 2023
YOUNG CONCRETE RESEARCHERS, ENGINEERS & TECHNOLOGISTS SYMPOSIUM

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Lightweight aggregate manufacturing for use in structural concrete

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Abstract

In this paper the manufacturing process of lightweight aggregate for the use in structural concrete is discussed. A reference mixture was cast in this pilot study to give a preliminary indication of the possibility of an ultra-lightweight structural concrete mixture. This paper outlines the materials and procedures used to create lightweight aggregate from local waste materials. This paper aims to indicate whether lightweight aggregates made from waste streams can be used in structural concrete. Although the initial results from this pilot study is promising, further research is needed to refine the properties of the lightweight aggregate.

Keywords: lightweight aggregate, lightweight concrete, manufactured aggregate, waste recycling

1. INTRODUCTION

The environmental impact of the construction industry is large. The construction industry was responsible for 39% of the total global yearly energy-related CO_2 emissions in 2018 [1]. Every effort should be made to ensure that the environmental impact of the construction industry is reduced. Lightweight concrete can be used to reduce the environmental impact of concrete. If the own weight of the structure is reduced the total load that the structure needs to support is reduced, therefore elements with smaller cross sections can be used. This will reduce the total volume of concrete used during construction and subsequently reduce the CO_2 emissions during construction.

In South-Africa 32.7% of the fly ash produced by the coal-fired power stations is recycled [2]. Although there is an increase in recycling of glass in South-Africa only 44% of glass was recycled in 2020 [3]. These two waste materials were used as the main components of the lightweight aggregate proposed in this paper. The aim of this paper is to prove that these two waste streams can be utilised to manufacture lightweight aggregates for use in structural concrete.

2. LITERATURE REVIEW

Lightweight aggregates can be manufactured from various materials. Tuan et al. [4] used wet sewage sludge and waste glass powder to manufacture lightweight aggregates. The effect of sintering temperatures between 830°C and 1100°C were also analysed during the study. It was found that an increase in sintering temperature led to an increase in bulk density of the lightweight aggregate.

Liu et al. [5] manufactured lightweight aggregates from waste glass and engineering muck. Lightweight aggregate with an apparent density of 1.461 g/cm^3 and a single-particle crushing strength of 20.81 MPa was manufactured. The improved mechanical properties were attributed to the formation of diopside in the aggregates. They found that an increase in glass content in the aggregate mixture led to an increase in diopside formation.

Li et al. [6] studied the influence of sintering temperature and dwelling time on the characteristics of lightweight aggregates produced from sewage sludge and waste glass powder. An increase in sintering temperature decreased the water absorption, density and compressive strength of the particles.

Fly ash has been used as the main component of manufactured aggregates in studies performed by various authors [7, 8].

Table 1 is a summary of different lightweight concrete mixtures made with glass aggregates.

Table 1: Summary of different glass aggregate concrete mixtures

Reference	Strength (MPa)	Density (kg/m^3)
Tuan et al. [4]	49.46	1947
Yousefi et al. [9]	8.20	987
Yousefi et al. [9]	26.25	1769
Rumsys et al. [10]	35.1	1590

The aim of this study was to determine a suitable mixture composition for producing lightweight aggregate from local streams of waste that can be used to manufacture structural concrete.

3. EXPERIMENTAL SETUP

The lightweight aggregate was manufactured by combining fly ash, dolomite, waste glass, kaolin clay, water and sodium metasilicate pentahydrate ($Na_2SiO_3 \cdot 5H_2O$) in different proportions. The fly ash and waste glass are local waste materials included in the aggregate mixture for strength purposes. The kaolin clay (also a local waste material from the Taaifontein kaolin deposit) was included to aid with the formation of the aggregate balls. The dolomite and $Na_2SiO_3 \cdot 5H_2O$ were included in the aggregate mixture to assist with the formation of voids in the aggregate once the heating cycle commenced. Water was used during the manufacturing process to form the aggregate balls and for all aggregate mixtures 20% by mass was used.

Firstly, the optimal proportion of fly ash, waste glass and dolomite were determined. This was done with a design of experiments setup to vary all three variables simultaneously. The mass ratio of glass and fly ash to kaolin clay and dolomite was kept constant at 80:20. The dolomite % was varied between 0% and 10% of the total weight of the lightweight aggregate.

Within the glass and fly ash portion, the ratio of glass to fly ash was varied from 0:100 to 100:0. This method yielded aggregate mixtures named Mix 1 to Mix 9 as shown in Figure 1.

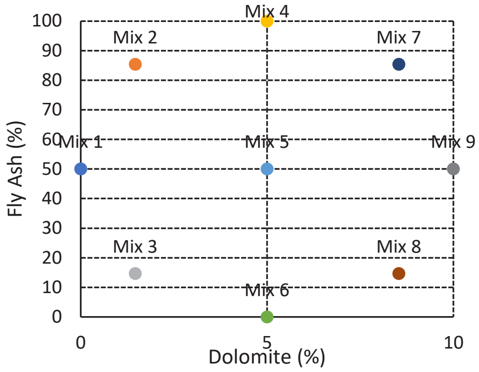

Figure 1*:* Design of experiments

The results from the initial design were analysed and it was determined that the optimal ratio of glass to fly ash is 85.36:14.64, but that the optimal dolomite percentage was not reached. For Mix 10 to Mix 12 this optimal glass to fly ash ratio was used and the percentage dolomite was increased with the same amount as for Mix 3 and Mix 8. Subsequently the percentage kaolin clay used was decreased. For Mix 11 and Mix 12 the percentage of kaolin clay used could not be decreased further. The same amount of kaolin clay as in Mix 10 was used for these two mixes and the mass ratios of glass and fly ash to kaolin clay and dolomite were changed to 72.93:27.07 and 65.86:34.14 respectively. The results from Mix 10 to Mix 12 were analysed and Mix 10 had the optimal percentage dolomite. Mix 10 was then used as the basis for the design of Mix 13 to Mix 17. In these mixes up to 15% in weight of $Na_2SiO_3{\cdot}5H_2O$ was added in steps of 3%. $Na_2SiO_3{\cdot}5H_2O$ was used as glass replacement.

3.1 Lightweight Aggregate Manufacturing Process

All the mixtures were manufactured using the same procedure. The waste glass, $Na_2SiO_3{\cdot}5H_2O$ and dolomite was milled in a ball mill whereafter it was sieved through a 150 µm sieve. All the dry constituents of the mixtures were pre-mixed in a disc granulator for a period of two minutes to ensure homogeneity. The disc granulator was set to rotate at 50 rotations per minute and was placed at an angle of 35° with respect to the horizontal. Water was added using a spray bottle. All mixtures were heated to 100°C for 2 hours whereafter it was heated to 850°C at a heating rate of 999°C/hr and kept there of 1 hour. The vents of the oven were then opened to allow the oven to gradually cool down. The lightweight aggregates were removed from the oven the following day once the oven had cooled to room temperature.

3.2 Lightweight Aggregate Testing Procedure

All mixtures were subjected to the same tests. Grading analysis, aggregate impact value (AIV), moisture absorption (MA) and relative density (RD) tests were performed on all the mixtures. AIV was chosen as the metric to determine the relative strength of the lightweight aggregate mixtures since it requires a smaller sample size than the regularly used 10% FACT and Aggregate Crushing Value tests. Since these lightweight aggregates are in the prototype phase the smaller sample size used for AIV testing is beneficial for rapid testing and iterations [11].

The AIV tests [12], MA tests [13] and grading analyses [14] were conducted. Various RD test methods were used. For Mix 1 to Mix 12 the wax coating method was used. For Mix 13 to Mix 17 the wax method could not be used. For these mixes the water displacement method was used. The lightweight aggregates were weighed dry, then placed in water under 80 kPa of pressure for 4 hours whereafter the aggregates were fully saturated and therefore they sank.

3.3 Concrete Testing

To determine the strength of concrete containing manufactured lightweight aggregates, Mix 13 to Mix 17 were cast into respective concrete mixtures. A control concrete mix with dolomite aggregate was cast. The lightweight aggregate was used as coarse aggregate replacement due to the sizes that was manufactured and therefore all mixes contained dolomite sand as the fine aggregate. Only compressive strength, saturated and dry density of the mixtures were determined as this study only aimed to provide a proof of concept.

Three cubes were cast for 7-day strength testing and two for the dry density calculation. All 5 cubes were cured in water at 25°C. After seven days of curing two cubes were placed in an oven at 60°C for a week to dry whereafter the dry density of the concrete mix was determined. The lightweight aggregate was placed in water 24 hours before casting to ensure that they were saturated. The concrete mixtures are shown in Table 3. The coarse aggregate is shown in l/m3 since the mass of the coarse aggregate varied. A water cement ratio of 0.5 and a coarse aggregate to fine aggregate ratio of 60:40 were used.

Table 2: Concrete mix design

Mix	Control	Mix 13	Mix 14	Mix 15	Mix 16	Mix 17
Water (kg/m^3)	230	230	230	230	230	230
Cement (kg/m^3)	460	460	460	460	460	460
Fine aggregate (kg/m^3)	713	713	713	713	713	713
Coarse aggregate (l/m^3)	374	374	374	374	374	374
Coarse aggregate (kg/m^3)	1070	370	302	252	269	307
Absorbed water (kg/m^3)	0	113	101	104	113	107
Casting density (kg/m^3)	2473	1886	1806	1759	1785	1817

4. RESULTS AND DISCUSSION

4.1 Aggregate Testing

The aggregates that were manufactured were coarse and not suitable for fine aggregate replacement. For fine aggregate replacement the size of the manufactured aggregates must be reduced. The mean aggregate size of each aggregate mixture was 6.7 mm – 9.5 mm. The AIV, RD and MA test results are shown in Figure 2a, b and c respectively. The AIV and MA increased as the percentage fly ash increased and the dolomite content did not have a considerable influence on the AIV and MA. The RD of the lightweight aggregates decreased as the percentage fly ash and dolomite increased. As the percentage dolomite increased the RD of the lightweight aggregate became less dependent on the percentage fly ash. Based on these results the dolomite content was increased as the optimal percentage dolomite was not yet reached in the initial design. Due to the high strength of aggregates with low fly ash compositions and the decreasing effect of the fly ash percentage on the RD as the percentage dolomite increases, a low fly ash percentage was used for the next aggregate designs.

The AIV results of mixtures 3,8,10,11 and 12 are shown in Figure 3. There is a slight increase in AIV as the dolomite percentage increased, but all these values are low. For comparison, the AIV of dolomite was 13 when it was tested. The 15.62% dolomite mixture has the smallest RD. This mixture was used as the base mixture for the mixtures where $Na_2SiO_3{\cdot}5H_2O$ was added since this mixture was the lightest.

Figure 4a shows the AIV results of the mixtures containing $Na_2SiO_3{\cdot}5H_2O$ (Mix 13 – Mix 17). There is a substantial increase in AIV as the percentage $Na_2SiO_3{\cdot}5H_2O$ increased. There is a clear peak at 9% whereafter the AIV reduced as the percentage $Na_2SiO_3{\cdot}5H_2O$ increased. In Figure 4b the RD and MA of these mixtures are shown. The same trend in the AIV results can be seen in the MA results. This trend coincides with the initial decrease and subsequent increase in RD as the percentage $Na_2SiO_3{\cdot}5H_2O$ increased. The RD increasing at higher percentages of $Na_2SiO_3{\cdot}5H_2O$ can be due to the heat cycle being suboptimal.

The MA of the aggregates is highly dependent on the surface of the aggregate. Since the aggregate is porous on the inside it absorbs significantly more water if the surface of the aggregate is also porous. The surface porosity of the aggregates should be reduced in future to decrease the MA of the aggregates.

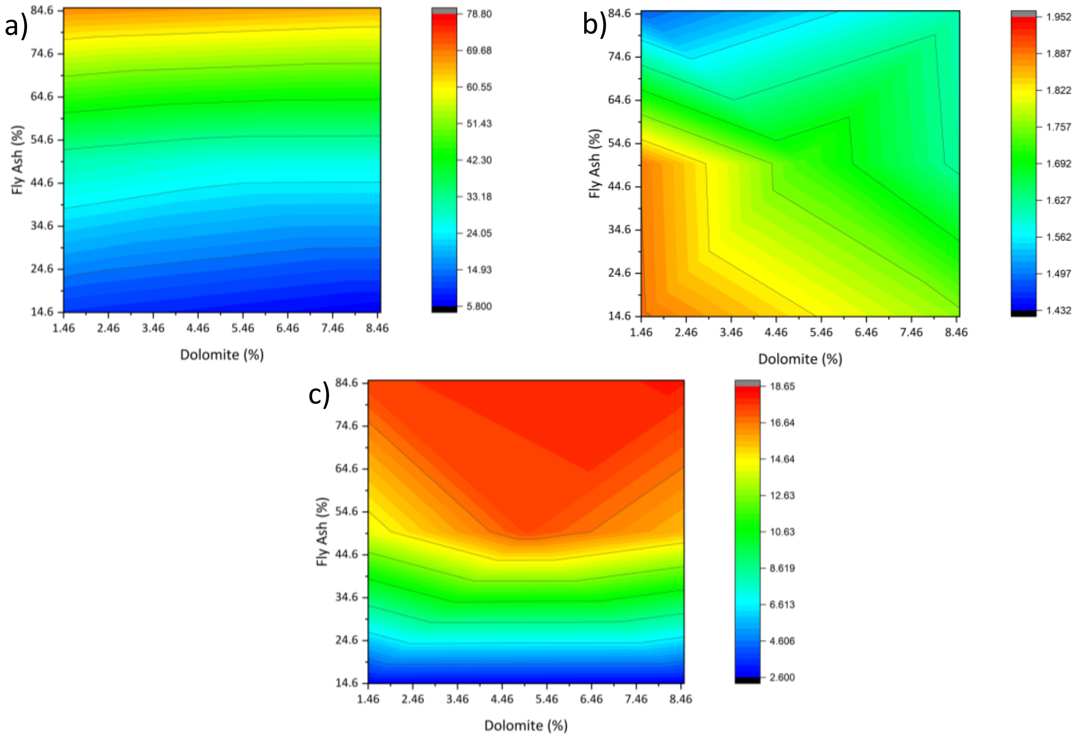

Figure 2: Design of experiments aggregate results a) AIV (%) b) RD and c) MA (%)

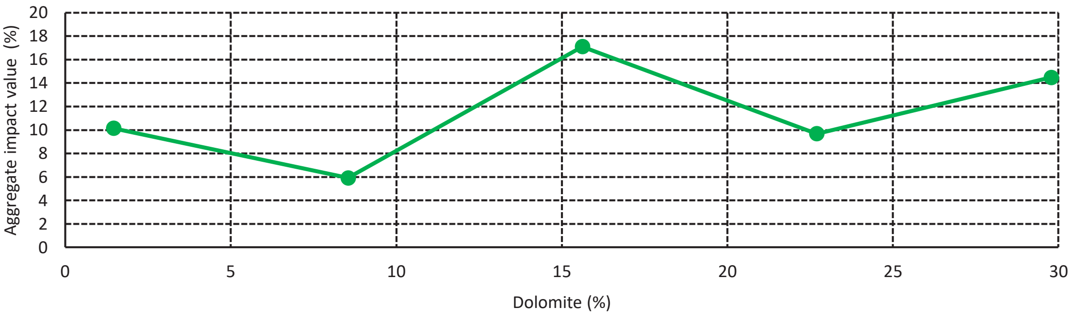

Figure 3: AIV results of the dolomite optimisation mixtures

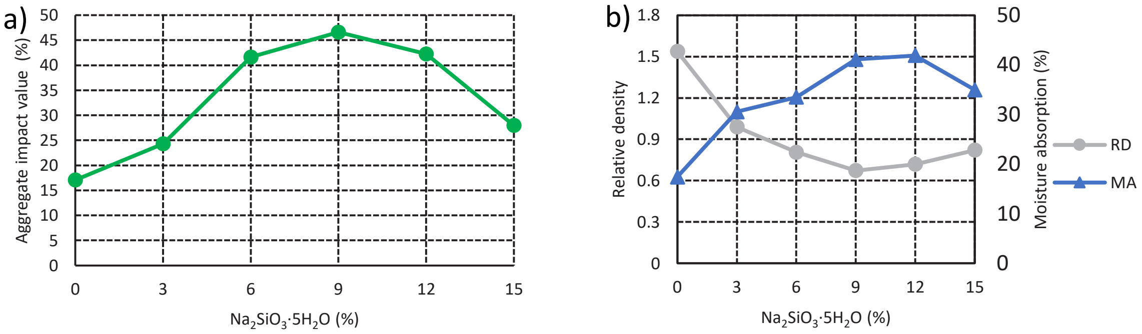

Figure 4: AIV, RD and MA results of the $Na_2SiO_3·H_2O$ mixtures

4.2 Concrete Testing

Figure 5a indicates that the strength of the concrete decreased as the saturated density of the concrete decreased. The same trend is observed if the dry density is used as shown in Figure 5b. In both instances there is a steep decline in strength for a marginal reduction in density among the lightweight aggregate concrete mixtures. Figure 6 illustrates that the lightweight aggregates with the highest AIV has the lowest strength. This supports the trend seen in Figure 5a and b. In Figure 6 the relationship between the lightweight aggregate AIV and concrete strength is linear. Therefore, this can be used to estimate the strength of the concrete cast with a lightweight aggregate based on the AIV of the lightweight aggregate.

In Figure 7 the strength of the concrete initially decreased as the percentage $Na_2SiO_3·5H_2O$ increased, but at higher percentages $Na_2SiO_3·5H_2O$ the strength of the concrete increased. This trend coincides with the saturated density reduction and increase. This also coincides with the trend of the AIV with increasing percentages of $Na_2SiO_3·5H_2O$ seen in Figure 4a. In Figure 8 it is shown that the strength of the concrete increased as the RD of the lightweight aggregates increased. This is to be expected since the lightweight aggregate is the reason for the reduction of the concrete density and therefore it will match the trends in Figure 5a and b. In Figure 8 there is no relationship between the RD of the lightweight aggregates and the air entrapped in the concrete mixture. Figure 9 illustrates the difference between the dry- and saturated densities of the concrete mixtures. The dry densities of the concrete falls in the range of structural lightweight concrete [15]. The lightweight aggregate concrete cubes failed through the aggregates and therefore the reduction in aggregate strength caused a significant reduction in concrete strength. The strength of the paste of the lightweight aggregate concrete can be reduced since the lightweight aggregate is governing the strength of the concrete.

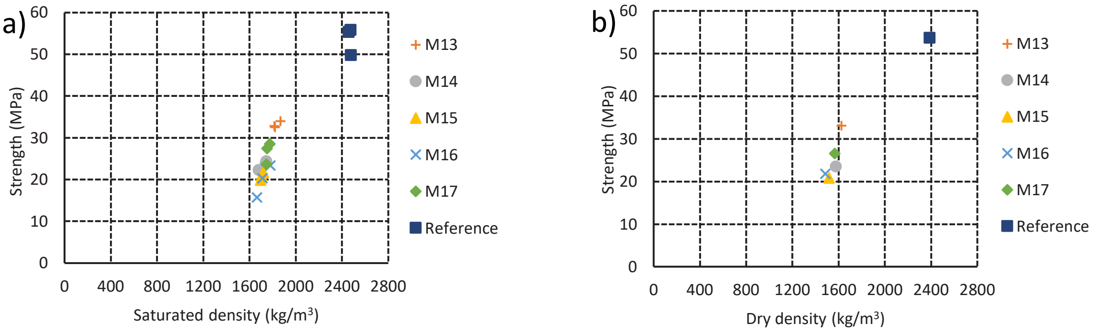

Figure 5: Strength of the concrete mixtures as a function of saturated and dry density

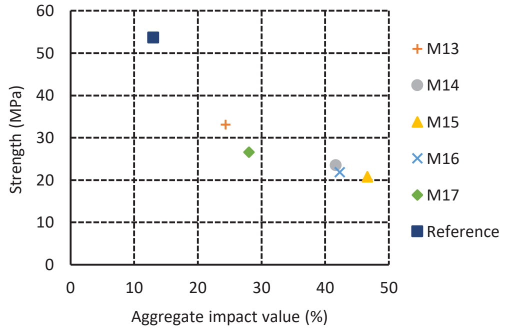

Figure 6: Strength of the concrete mixtures as a function of AIV

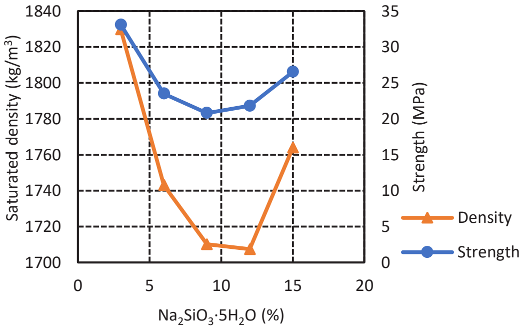

Figure 7: Density and strength of the concrete mixtures as a function of $Na_2SiO_3{\cdot}5H_2O$ content

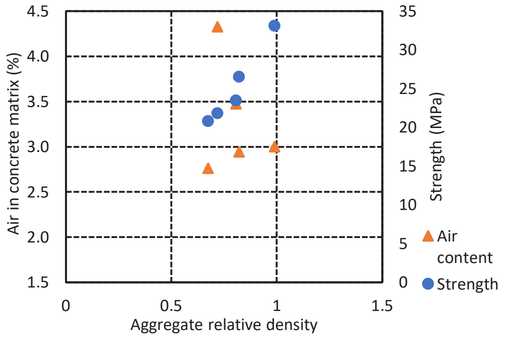

Figure 8: Air content and strength of the concrete mixtures as a function of the RD of the lightweight aggregates

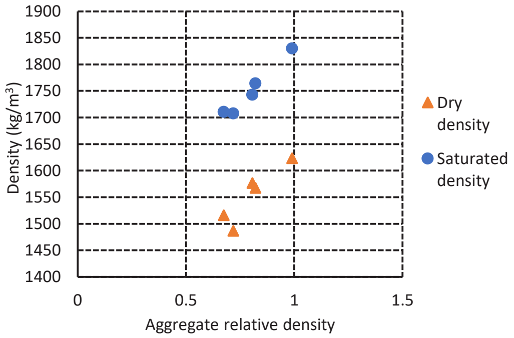

Figure 9: Dry and saturated density of the concrete mixtures as a function of the RD of the lightweight aggregates

5. CONCLUSIONS AND RECOMMENDATIONS

It is possible to produce lightweight aggregates that contain 67.8% South-African waste materials that can be used in structural concrete. A high mass ratio of glass improved the strength of the lightweight aggregates and the addition of $Na_2SiO_3{\cdot}5H_2O$ greatly reduced the

RD of the lightweight aggregate. Further investigation into the concrete properties should be done to determine if the concrete adheres to all the requirements of the structural concrete design code. Factors influencing size of aggregates produced should be analysed. The surface porosity of aggregates should be reduced. The concrete mixture should be optimised before structural concrete tests are performed on the concrete. A complete cost comparison to natural aggregates should also be done to ensure that the lightweight aggregates are affordable. This might require further optimisation of the lightweight aggregate mixture.

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