An Investigation of Partial Replacement of Fine Aggregate with Recycled Plastic Supported by Silica Fume and its Effect on Compressive Strength and Weight

Nigel Mugliett, Roderick Bonnici*
Corresponding Author: Roderick.Bonnici@mcast.edu.mt
*Institute of Engineering and Transport, MCAST

Abstract: Concrete is one of the main construction materials used in the building industry where it is projected that the revenue of manufacture of ready-mix concrete will amount to approximately 37.5 million dollars by 2022 in the local sector. In addition, plastic waste is another important contributor to the waste pollution since locally only 7% of such waste is recycled. This study is based on the partial replacement of aggregate by means of recycled polycarbonate plastic bottles while attaining the required structural compressive strength. Dolomite, which is an imported aggregate, and silica fume, which is a cementitious material, were used to attain a more appropriate concrete mixture.

A total of six concrete mixtures were designed for the purpose of the research by varying the proportion of polycarbonate and fine aggregate. A uni-axial compressive strength test was performed after 7 and 28 days from the cube casting where a maximum of 63.2N/mm² was attained with a control mixture made of dolomite as the coarse aggregate. Results also showed that the compressive strength decreased with the addition of plastic as a partial replacement of fine aggregate.

Statistical analysis by means of an independent sample T-test showed that no significant difference in compressive strength was present between the silica fume mixture and the 5% fine aggregate replacement mixture. The results also showed that compared with the control mixture, the silica fume mixture was significantly weaker at 7 days, but no significant difference resulted at 28 days. Considering the results attained, one may easily note that there was a significant relationship between the percentage of plastic and the compressive strength. A regression analysis was used to observe such a relationship. Moreover, the result showed that a replacement percentage of 48% results in a suitable compressive strength of 10.19N/mm², where such concrete can be utilised for non-structural purposes.

From the results obtained, it was also observed that the final mass of the concrete blocks decreased as the plastic percentage increased. In relation, by maintaining a constant volume between all the samples, the hardened density of the samples also decreased with the increase in plastic percentage.

Keywords: Recycled Polycarbonate Plastic; Dolomite; Silica fume; Compressive strength
Introduction

When comparing concrete to other building materials typically used, statistics show that concrete is used twice as much as all the other building materials combined. Following the usage of water, concrete is the second most used material worldwide. Having such popularity, it is envisioned that concrete will remain as one of the most used materials in the construction industry (Zongjin 2011). Considering such aspects, it could be highly beneficial if some of the constituents making up the concrete mixture can be replaced by more sustainable materials which result in a more sustainable concrete mixture.

The use of waste materials and the integration of such materials into the concrete mixture can be one of the sustainable approaches. Integration can help to reduce the use of natural resources which require an energy-demanding production process to be prepared for mixing purposes. A very common type of waste amongst products is plastic waste. Plastic waste is known to be very harmful to the environment if disposed of inappropriately. This is because of the long period required for plastic to disintegrate (Huysman, et al. 2017).

The main scope of the following research is to reduce the negative impact caused by the disposal of plastic on the environment while also introducing a more sustainable and lighter concrete mixture that performs better or similar in comparison to the traditional concrete mixture.

Research Goals

During the initial phases of this dissertation, hypotheses, aims, and objectives were formulated so that an appropriate research methodology could be conducted. The research question states that:

‘If imported aggregate, supported by silica fume and varying the ratios between fine aggregate and Polycarbonate plastic, would it be possible to achieve a constant compressive strength?’

Such a research question formulated two hypotheses which included a null hypothesis ($H_0$) and an alternative hypothesis ($H_1$).

For the purpose of this research, three aims were formulated as follows:
1. Obtain and provide an alternative to the traditional mixture where the fine aggregate is partially replaced with plastic particles.
2. Determine the range of percentages where sand can be partially replaced by shredded polycarbonate plastic.
3. Identify the change in the compressive strength, if any, when exceeding the 10% replacement mark identified in previous research works.
Literature Review

**Figure 1: Literature map**

**Introduction**

The demand for concrete continues to rise every day because of the ever-increasing population and the standards of living (Zongjin 2011). As a material, concrete is known to be a composite made up of constituents including different graded aggregates, cementitious materials, and water for hydration (Zongjin 2011). When such constituents are mixed, transferred to a form, and allowed to cure, a hardened structure is obtained. The chemical reaction resulting from water and cement mixing causes such hardening which increases stress over time (Gambhir 2013). The most important properties of concrete are known to be the strength and durability which are obtained and controlled by the cement and the water content within the mixture (Hubertus 2006).

The strength that the concrete can attain is highly dependent on the process of production, the quality of the constituents, and the proportion of the mixture (Gambhir 2013).
The Constituents of Concrete

Cement

A wide variety of cement types are available within the construction market, but the most common type is known as the Ordinary Portland Cement. The types of cement are divided into different strength classes represented as 32.5, 41.5 and 52.5.

Each strength class is further divided based on its initial strength. Cement having a standard initial strength is provided with the letter ‘N’ while cement having a higher initial strength is identified with the letter ‘R’ (Barkauskas et al. 2013). Although all the constituents are important in the concrete mixture, cement is one of the most important. Cement has multiple functions, the first being binding the fine and the coarse aggregates together. The second function is to fill up the voids formed between the particles of the coarse and fine aggregate so that a compact mixture structure can be obtained. From all the components, cement is known to be the only component that is controlled through science (Gambhir 2013).

Aggregate

Aggregates are also an important constituent in concrete. Making about 70% to 80% of the total volume of concrete, aggregates greatly affect the characteristics and properties of concrete (Shetty & Jain 2019). Making up such a large percentage of the concrete, it is highly important that aggregates respect certain requirements such as strength, size, shape, and grading (Nayak & Jain 2012). Apart from the steadiness and toughness that aggregates provide, aggregates are also very cheap compared to cement. Different sizes of aggregates are used to increase the density of concrete and minimize the void space in the final product. Aggregate larger than 4.75mm is classified as coarse aggregate while that smaller than 4.75mm is classified as fine aggregate (Gambhir 2013). The main function of fine aggregate is providing a workable and a uniform mixture while also preventing the mixture from experiencing segregation between the cement paste and the coarse aggregate (Gambhir 2013). In a concrete mixture, if the aggregate is packed in a denser manner, the durability and the economy of the concrete mixture are known to be improved (Darwin et al. 2016). Produced naturally, aggregates may have a variety of properties, meaning that appropriate tests must be performed to ensure good quality of aggregate (Shetty & Jain 2019).

Water

In addition to cement and aggregates, a concrete mixture requires the addition of water. It is highly important that the water added to the concrete is clean and free of any oils, acids, and salt. Typically, the water being added must be suitable for drinking purposes (Woodson 2012). The addition of water in a concrete mixture is as important as the addition of cement since water affects the condition of both fresh and hardened concrete (Aitcin & Flatt 2015). Water can be a complex addition because of all the forms of hidden water within the fine and coarse aggregate. It is highly important that the water content is adjusted depending on the properties of the aggregates (Aitcin & Flatt 2015).

A percentage of the included water results in the hydration of the cementitious materials initiating binding of the aggregates. The residual water lubricates the fine and the coarse aggregates which leads to the workability of a concrete mixture. The addition of water in the mixture results in cement paste which starts to set so that hydrated cement can be achieved after a few hours (Hubertus 2006).
Cement requires approximately three tenths of its weight equivalent to water to start the hydration process, meaning that the minimum water to cement ratio is 0.30 (Gambhir 2013). At a water to cement ratio of 0.30, the mixture is very tough to work with, meaning that a higher ratio is required. The process of addition of water to a mixture must be conducted carefully since the more water that is added, the weaker the final product will be, meaning that the water to cement ratio is highly dependent on the concrete grade (Gambhir 2013).

**Dolomite Aggregate**

Dolomite is typically referred to by geologists as dolostone or the dolomite rock. Dolostone can be identified as a sedimentary rock, meaning that such types of rocks are formed from the accumulation of other minerals located on the earth’s surface (King 2005).

Dolomite rock is mainly composed of a mineral known as dolomite which is made up of the chemical formula CaMg(CO₃)₂. The Dolomite mineral is obtainable from sedimentary basins found worldwide. Such a mineral is known to be formed by the build-up of lime mud, limestone, and groundwater which is considered to be highly rich in magnesium (King 2005).

Comparing dolostone to limestone, both these types of stones are made up of approximately the same colour except dolostone is known to have a slightly darker colour than limestone. These two types of stones also contain approximately the same hardness which can be seen on the Mohs hardness scale. From the scale, limestone is known to have a Mohs hardness of 3 while dolomite rock has a Mohs hardness of 3.5 to 4 (King 2005).

**Silica Fume**

Silica fume is a by-product that is created by the industry of silicon and ferrosilicon production. Silica fume is created from oxidized silicon dioxide (SiO₂) which condenses with low-temperature zones and ends up producing very small particles of non-crystalline silica (Newman & Choo 2003). Ferrosilicon alloy, which approximately contains 50% silicon, results in a by-product that contains very low silica content and is also less pozzolanic than the by-product created from other types of alloys. Silica fume can also be acknowledged as micro silica, volatilized silica, and silica dust. The term silica fume is typically used to identify the condensed silica fumes having higher quality than the others, meaning that they can be used by the construction industry (Newman & Choo 2003). The main colour of silica fume is that of a dark grey colour, but it can also vary between a premium white colour and a darker grey colour (Siddique 2011).

**The Use of Silica Fume in Concrete**

Silica fume is known to contain pozzolanic properties, meaning that it can be incorporated within a concrete mixture. Adding silica fume in a concrete mixture results in a reaction with the lime content increasing the strength of concrete. Silica fume can also be used to complement the compound of the cement found within the same concrete mixture (Newman & Choo 2003). The addition of silica fume as a partial replacement of cement, reduces the environmental impact resulting from the production of cement. In the United Kingdom, the typical percentage replaced is 10% by the mass of cement (Georgopoulus & Minson 2014). The introduction of silica fume to a concrete mixture enhances its mechanical properties. Such an enhancement occurs from the reaction between the silica fume and the existing silica found in pozzolans. The reaction allows the formation of extra calcium silicate hydrate which is highly important in the hydration phase of concrete (Pradhan & Dutta 2013).
The durability of concrete is again affected by the introduction of silica fume to the concrete mixture. Durability increases by the reduction of the permeability of the concrete and by the refining of the pore structure. Both improvements result in a concrete mixture that is highly resistant to sulphate attack when compared to a traditional concrete mixture. In addition, reduction of sulphate attack reduces cracks in the concrete structure allowing for better protection of the enclosed reinforcement from corrosion (Rasol 2015).

**Past Studies Assessing the Addition of Silica Fume in Concrete**

As identified by Farooq et al. (2019), the addition of E-plastic waste into a concrete mixture resulted in a decrease in the compressive strength of the final product. In such a study, the researchers introduce the use of silica fume which is known to contain highly pozzolanic properties, meaning that the compressive strength of concrete increases by the addition of silica fume.

From such observations, the researchers concluded that with the replacement of 10% of the cement content by silica fume, the optimum strength was achieved. The researchers also concluded that for the replacement of fine aggregate with E-plastic to be considered as an effective substitution, the addition of silica fume is highly important.

Ramana and Harini (2015) observed the impact on the compressive strength when partially replacing fine aggregate with recycled plastic. The researchers concluded that no significant difference resulted from the replacement of fine aggregate up to a replacement of 6%. After such a percentage, the results showed a gradual decrease in the compressive strength. Ramana and Harini (2015) conducted further research about the effect on the compressive strength when partially replacing sand by the maximum percentage of 20%, and 5%, 10%, or 15% addition of silica fume. The researchers concluded that by the addition of silica fume, the concrete experienced a 22.5% increase in compressive strength when compared to the mixture which did not include silica fume.

Srivastava et al. (2014) assessed the suitability of silica fume in the production of concrete. By partially replacing cement by multiple percentages, the researchers concluded that the optimum replacement was 5% from the weight of the cement resulting in a compressive strength which was 12.5% higher at seven days and 18.18% higher at twenty-eight days. Srivastava et al. (2014) also concluded that percentages higher than 10% result in a decrease in compressive strength. The researchers added that such a decrease resulted due to the replacement of the primary binder being cement, causing the strength to decrease.

The increase in compressive strength by the addition of silica fume was also confirmed by Mazloom et al. (2004). The researchers concluded that the compressive strength of the concrete containing between 6% and 15% at seven days was about 5N/mm² higher than the control mixture. After twenty-eight days the difference in compressive strength when having 10% silica fume was approximately 10N/mm² higher than the control mixture. Mazloom et al. (2004) also concluded that the addition of silica fume in concrete greatly affects the early strength of the concrete, meaning that from ninety days onwards, there was no significant difference in the compressive strength.

**The Issue of Plastic Waste**

The issue of plastic waste is a highly known issue around the world. This is because such an issue causes a high danger to the environment. Plastic waste requires a large landfill and a high cost of disposal resulting in the difficulty of landfilling. Guglielmi (2017) predicted that by the 2050s the world would have produced approximately twenty-six billion tonnes of plastic waste, half of which will be dumped in landfills and illegally dumped in the environment.
Considering these two factors, if not recycled, plastic usually ends up being illegally dumped causing health hazards due to the time required for such plastic to disintegrate (Huysman et al. 2017). The time required for plastic to disintegrate is highly dependent on the level of durability required by the produced plastic. Typically, plastic is designed to last for a long period but despite such a design, plastic is typically used for short-term purposes such as plastic bottles which are used once and dumped (ScienceForEnvironmentPolicy 2011).

The production of plastic waste is always expected to increase because of the introduction of new products made from plastic since it is a relatively cheap material. Such products also introduce new types of plastic which were never utilized and recycled before. The increase of plastic waste is highly worrying since the waste management capabilities of certain countries may not be adequate for the rate of increase in plastic waste. Plastic waste requires an urgent need of identifying alternative solutions such as the reusing of plastic waste in other applications such as incorporating plastic waste in a concrete mixture (Tayeb et al. 2020).

Different sectors within an industry will use different amounts of plastics depending on their products and labour methods. Through a study published in 2018, the researchers explain that the sector which utilizes plastic the most within the industry is the packaging sector which utilizes around 146 million tonnes per year, followed by the building and construction sector which uses approximately sixty-five million tonnes per year. Looking also at the plastic waste generated per person and the total plastic generated by countries, in Malta, a person generates approximately 0.21kg of plastic waste daily, which is a relatively high number when compared to larger countries such as Italy, Russia, and Sweden. In 2010, the Maltese island produced approximately 33,000 tonnes of plastic waste in a year while countries such as Ireland and Italy produced seven to fourteen million tonnes of plastic in a year. Haward (2018) explains that approximately eight to twenty-four tonnes of plastic waste enter the ocean within one minute. From such statistics, one can identify how problematic plastic generation and plastic waste are (Ritchie & Roser 2018).

Considering the global pandemic happening at present, the use of single-use plastic increased its popularity since consumers experienced an economic crisis which led to the consumer opting to use more affordable goods that are typically less environmentally friendly. The pandemic also caused people to utilize more take-out restaurants, which is very good for the economic sector but very bad for the environmental sector since such take-out restaurants contribute to the increase in single-use plastics (Ford 2020).

**Characteristics of Polycarbonate**

Polycarbonate plastic can be identified as a thermoplastic. The term thermoplastic can be defined as materials that become liquid at their respective melting points and gradually harden during the cooling process (Torgal et al. 2018). Such materials can undergo this type of cycle for more than one time without experiencing any significant degradation. Such a property allows thermoplastics to be highly recyclable. Other types of thermoplastics are Polyethylene (PET), which is the most common type of thermoplastic, and Acrylonitrile Butadiene Styrene (ABS).

Polycarbonate material is a naturally transparent and amorphous material, meaning that polycarbonate does not have a clearly defined shape or form. Being amorphous, polycarbonate can be used in situations where the material will experience higher temperatures than usual. This is possible since amorphous materials allow for a more extensive range between the temperature required for solid-state and that required to reach and exceed the melting point (Rogers 2015).
Considering the physical characteristics of such a plastic, polycarbonate can be identified as an engineering plastic where such plastics are typically used for robust applications such as impact-resistant surfaces. Polycarbonate is a very popular engineering thermoplastic used widely due to it having excellent toughness and stiffness, being cost-effective, having high recyclability potential, and being greatly resistant to fracture and impact (Jangbarwala 2017). Polycarbonate is also highly popular in engineering applications due to it being able to be moulded into any form and because of its exceptional performance (Zhang & Xu 2019).

**Partially Replacing Fine Aggregate with Plastic Particles**

Hannawi et al. (2010) formulated a comparison between two different types of thermoplastics. The main reason behind such comparison was that partial replacement of fine aggregate with plastic was mainly conducted using polyethylene and not polycarbonate. Such research was conducted by partially replacing fine aggregate with the same percentages from each type of thermoplastic. The researchers concluded that although both mixtures experienced a decrease in compressive strength, the final product containing polycarbonate plastic decreased the compressive strength less than the other mixture. Such a study concluded that it can be more beneficial if polycarbonate plastic is used instead of polyethylene plastic.

Martinez et al. (2017) conducted a research study about the impact on the compressive strength when fine aggregate is partially replaced with polycarbonate obtained from electronic waste. The researchers managed to obtain multiple results by replacing 1%, 3%, and 6% of the fine aggregate. From the study, the researchers concluded that the smaller the particle size of the plastic is, the higher compressive strength values can be achieved. Such a conclusion was obtained by using two different particle sizes of plastic aggregate being 3x1mm and 1.5x1mm. The researchers concluded that the optimum compressive strength of 28.2Mpa was achieved by partially replacing sand with 3% with 1.5x1mm plastic aggregate. The 28.2MPa reached resulted in a 20% increase in compressive strength from the control mixture. For an aggregate of size 3x1mm, the researchers concluded that the optimum replacement was that of 1% where a compressive strength of 25.2MPa was obtained from the concrete samples.

Cassar (2019) used polycarbonate plastic particles as a replacement of fine aggregate to assess the effect on the compressive strength due to such replacement. By partially replacing fine aggregate with a range of percentages from 5% to 15%, the researcher concluded that partially replacing 10% of the fine aggregate with polycarbonate plastic resulted in concrete which cannot be used as a load-bearing structure, meaning that the compressive strength did not surpass 25N/mm². Moreover, it was also concluded that the optimum percentage of partial replacement of fine aggregate is that of 5% by the volume of fine aggregate.

**Research Methodology**

*Introduction*

The research methodology highlights all materials used and tested to be able to produce a final concrete product and obtain relevant results. The process required to be able to achieve the desired mixtures involved the replacement with a certain percentage from the fine aggregate with recycled polycarbonate plastic supported by the use of silica fume.
**Figure 2: Methods of Data collection**

*Sampling Method for Aggregate*

**Figure 3.1: The Riffle box**

**Figure 3.2: Washing and preparing of aggregate**
Water Absorption and Particle Size Distribution of Coarse Aggregate

Figure 3.3: Submerged Material

Figure 3.4: Using vacuum pump and vibrating table

Figure 3.5: Arranged sieves prepared for the tests
Mix Proportions

The values within Table 1 summarise the mix proportions utilised for the purpose of this research. The database of a local material and concrete testing laboratory in addition to tables obtained from the British Standard Method of Mix Design were utilised to obtain the trial mixes listed below.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Mix 1</th>
<th>Mix 2</th>
<th>Mix 3</th>
<th>Mix 4</th>
<th>Mix 5</th>
<th>Mix 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C ratio</td>
<td></td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Cement content</td>
<td>kg</td>
<td>10.5</td>
<td>9.5</td>
<td>9.5</td>
<td>9.5</td>
<td>9.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Water Content</td>
<td>ltrs</td>
<td>4.7</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Foreign Sand 4/0 mm</td>
<td>kg</td>
<td>34.7</td>
<td>36.0</td>
<td>34.2</td>
<td>32.4</td>
<td>30.6</td>
<td>28.8</td>
</tr>
<tr>
<td>Foreign Aggregate 8/4 mm</td>
<td>kg</td>
<td>8.5</td>
<td>8.8</td>
<td>8.8</td>
<td>8.8</td>
<td>8.8</td>
<td>8.8</td>
</tr>
<tr>
<td>Foreign Aggregate 12/8 mm</td>
<td>kg</td>
<td>14.2</td>
<td>14.8</td>
<td>14.8</td>
<td>14.8</td>
<td>14.8</td>
<td>14.8</td>
</tr>
<tr>
<td>Recycled PC plastic</td>
<td>kg</td>
<td>0</td>
<td>0</td>
<td>0.759</td>
<td>1.517</td>
<td>2.276</td>
<td>3.035</td>
</tr>
<tr>
<td>MasterGlenium SKY 698</td>
<td>ltrs</td>
<td>0.105</td>
<td>0.113</td>
<td>0.113</td>
<td>0.113</td>
<td>0.113</td>
<td>0.113</td>
</tr>
<tr>
<td>MasterRoc MS 610</td>
<td>kg</td>
<td>0</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 1

Where,
- Mix 1: C25 control mixture
- Mix 2: C25 + 10% Silica fume
- Mix 3: C25 + 10% Silica fume+5% Polycarbonate
- Mix 4: C25 + 10% Silica fume+10% Polycarbonate
- Mix 5: C25 + 10% Silica fume+15% Polycarbonate
- Mix 6: C25 + 10% Silica fume+20% Polycarbonate

Mixing, Casting and Curing Procedure to Create Concrete Blocks

Figure 3.6: Mixing of the constituents
Figure 3.7: Casting of cubes
Figure 3.8: Curing of the samples
Concrete Testing

Testing of fresh concrete: Slump Test

Testing of Hardened concrete: Compression Test

**Figure 3.9:** Slump cone and base plate

**Figure 3.10:** Compression testing using a uniaxial compression machine

Analytical Analysis

**Independent Sample T-test**

Having two independent groups of data, the independent sample T-test was conducted to assess whether a null hypothesis can be accepted or rejected. The assumptions which were made in order to conduct the T-test were that the dependent variable within each group can be normally distributed and that the population variance of the two groups is homogenous (Laerd Statistics 2018). The independent sample T-test was repeated for 15 times using a confidence level of 95% for every test. The test was used to compare the mean compressive strength of the C25 mixture and the C25+10% silica fume mixture followed by comparing all of the other mixtures to the C25+10%SF mixture at both 7 and 28 days. The test was further on repeated for the comparison of the mean weight between the blocks.

The T-test was initiated by forming the null ($H_0$) and the alternative hypothesis ($H_1$) where:

- $H_0$: $u_1 = u_2$
  - and
- $H_1$: $u_1 \neq u_2$

To be able to calculate the T-test value, the standard deviation for each group had to be calculated using:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$
Where:

\[ s = \text{Standard deviation} \]
\[ n = \text{Size of the sample} \]
\[ x_i = \text{Each value of the data} \]
\[ \bar{x} = \text{The mean of each group} \]

To calculate the T-test value the following formula was used:

\[
t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \]

Where:

\[ \bar{x}_1 = \text{The mean of sample 1} \]
\[ \bar{x}_2 = \text{The mean of sample 2} \]
\[ s_1 = \text{Sample standard deviation 1} \]
\[ s_2 = \text{Sample standard deviation 2} \]
\[ n_1 = \text{Sample size 1} \]
\[ n_2 = \text{Sample size 2} \]

The final part of the T-test required to determine the degrees of freedom by using:

\[ DF = n_1 + n_2 - 2 \]

The degrees of freedom were used to determine the critical value from the t distribution table for a one-tailed T-test which was compared to the test statistic calculated to determine whether the value lies within the acceptance or the rejection region. The test was then concluded by identifying whether the null hypothesis \( H_0 \) is rejected or accepted.

**One-Way ANOVA test**

The one-way ANOVA test was utilized to assess whether there was a significant difference in compressive strength between three or more groups (Zach 2020). For the purpose of this dissertation, the means of the compressive strength of each group were compared to each other to identify if there was a significant difference in the results obtained at 7 and 28 days. To perform the test, the null and alternative hypothesis were formulated as follows:

\( H_0 \): There is no difference in the compressive strength after 7 days between the means of all the mixtures.

\( H_1 \): There is a difference in the compressive strength at 7 days between the means of all the mixtures.

And

\( H_0 \): There is no difference in the compressive strength after 28 days between the means of all the mixtures.
H₀: There is a difference in the compressive strength at 28 days between the means of all the mixtures.

Following the hypothesis, the Regression Sum of Squares (SSR) was calculated using:

\[ SSR = n \sum_{i=1}^{n} (\bar{x}_i - \bar{x})^2 \]

Where, \( n \) = The sample size of each group  
\( \bar{x}_i \) = The mean of the respective group  
\( \bar{x} \) = The overall mean

The Error Sum of Squares (SSE) was calculated using the following formula:

\[ SSE = \sum_{i=1}^{n} (x_i - \bar{x}_i)^2 \]

Where, \( x_i \) = The \( i^{th} \) observation of each group  
\( \bar{x}_i \) = The mean of the group respectively

The Sum of Squares (SST) was then calculated using SST = SSR + SSE

The previous calculation was followed by creating a table as follows:

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Squares</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2**

Where,  
DF treatment = number of groups - 1  
DF error = total observations - number of groups  
DF total = total observations - 1  
MS Treatment = SSR/DF Treatment  
MS Error = SSE/DF Error  
F = MS Treatment/MS Error

The F statistic value was compared to the F critical value found within the F distribution table using a significance level of 0.05, DF₁ = DF treatment of 5 and DF₂ = DF Error of 12. The One-Way ANOVA test was concluded by rejecting or accepting the null hypothesis depending on the F critical value obtained from the distribution table.
Regression Analysis

The regression analysis is a statistical tool used to observe the relationship between a dependent and an independent variable. The regression analysis determines how the dependent variable changes when the independent variable is modified (Budio et al. 2013). For the purpose of this research, the dependent variable was the compressive strength, and the independent variable was the replacement of fine aggregate with plastic.

The regression analysis formula formulated by the graph in Microsoft excel was in the form of:

\[ Y = a + bX + E \]

Where,
- \( Y \) = dependent variable
- \( a \) = intercept
- \( b \) = gradient
- \( X \) = independent variable
- \( E \) = residual

Analysis and Discussion

Descriptive Results

Moisture Content

The moisture content percentages obtained from aggregate testing can be observed in Figure 4.1. The moisture content of the fine aggregate was determined to be 2.29% which can be considered relatively high when compared to the coarse aggregate. The moisture content of sand is expected to be in the range of 2% - 6% because of its fine particles. The moisture content of the two types of aggregate having 0.96% and 0.88% was relatively close. Plastic aggregate was assumed to have 0% moisture content since plastic is a man-made material having properly designed properties.

Water Absorption

The British Standard BS8007 states that aggregates suitable for concrete mixtures should not exceed 3% water absorption. By using imported aggregate, such a standard
was respected as can be seen in Figure 4.2 below. The highest percentage of absorption was obtained by the 4-8mm coarse aggregate at 1.05% while the lowest percentage was obtained by the 8-12mm coarse aggregate at 0.78%. As explained, being a man-made material, polycarbonate plastic does not absorb water.

![Water Absorption Graph]

**Figure 4.2: Water absorption of dolomite aggregate and polycarbonate**

**Particle Size Distribution**

A standard range of sieves were used to determine the size distribution of the three types of aggregate. As can be observed in Figure 4.3 below, the 6.3mm sieve was the first sieve to retain fine aggregate while the 14mm and the 16 mm sieves were the first sieves to retain coarse aggregate respectively.

![Particle Size Distribution Graph]

**Figure 4.3: Particle size distribution of all aggregate sizes**

**Slump**

The mixture was designed to satisfy an S4 slump class meaning that the slump value for each mixture needed to be between 160mm and 210mm. The slump of the six mixtures varied from 170mm to 200mm as can be observed in Figure 4.4 below. The smallest slump value was acquired by the C25+10%SF+15%PC mixture at 170mm while the highest was 200mm obtained by the C25+10%SF+10%PC mixture.
Figure 4.4: Slump value for all six mixtures

Compressive Strength (7-day)

As can be observed in Figure 4.5 below, the C25 control mixture managed to obtain the highest compressive strength after 7 days followed by the mixture containing 10% silica fume. The average compressive strengths for the two mixtures were 53.2N/mm² and 44.87N/mm² respectively which are relatively distant from each other. The introduction of the plastic aggregate as a replacement of the fine aggregate decreased the compressive strength of the concrete as the percentage increased. Partially replacing fine aggregate with only 5% polycarbonate plastic resulted in a relatively similar compressive strength of 43.9N/mm² to the mixture having only 10% silica fume. The C25+10%SF+10%PC and the C25+10%SF+15% mixtures also managed to obtain a very similar average compressive strength of 34.5N/mm² and 34.3N/mm² respectively. The least value of compressive strength was obtained when replacing 20% of the fine aggregate with the plastic aggregate resulting in only 31N/mm².

Figure 4.5: Compressive strength at 7-days

Compressive Strength (28-days)

Similar to the compressive strength after 7 days, the compressive strength after 28 days also decreased as the plastic percentage increased. The highest compressive strength
was obtained by the control mixture at 63.3N/mm² similarly followed by the silica fume mixture at 62.8N/mm². Compared to the 7-day compressive strength, the silica fume mixture managed to obtain a value which is relatively close to the control mixture. Similar to the 7-day compressive strength, 5% replacement did not cause a drastic decrease in compressive strength from the mixture containing silica fume only. As the plastic percentage increased from 5% to 10%, a drop in the compressive strength of 10N/mm² was observed resulting in the C25+10%SF+10%PC mixture obtaining 49.2N/mm². As can be identified in Figure 4.6 below, the least compressive strength value was obtained by the C25+10%SF+20%PC mixture at 41.8N/mm².

Figure 4.6: Compressive strength at 28-days

Weight of the Samples

As can be observed in Figure 4.7 below, as expected, the difference in weight between 7 and 28 days was practically null. The C25 control mixture was the heaviest of the six blocks weighing 8.5kg, while the lightest block, which was made up of a mixture of C25+10%SF+20%PC, weighed at 7.69kg. Such a result was expected due to the plastic particles weighing less than the fine aggregate particles. Similar to their respective compressive strengths, the C25+10%SF and C25+10%SF+5%PC blocks weighed the same implying that 5% replacement does not affect the weight of the final product.

Figure 4.7: Final weight of the samples
Density of the Hardened Blocks

The highest density obtained from the blocks was that of 2517.5 kg/m³ by the C25 control mixture while the lowest density was that of 2271 kg/m³ obtained by the C25+10%SF+20%PC mixture. Such values are highly dependent on the weight of the blocks meaning that having the same volume, the higher the weight of the block, the higher the final density will be. As can be observed in Figure 4.8, the C25+10%SF+5%PC and the C25+10%SF+10%PC mixtures have very similar densities due to them weighing practically the same. From such an observation, it was concluded that the higher the percentage of replacement, the lower the density of the hardened material will be.

![Density at 28 days](image)

**Figure 4.8: Density of the samples at 28 days**

**Analytical Analysis**

**Independent Sample T-Test for 7-day Compressive Strength**

By forming the null and the alternative hypothesis:

- $H_0$: There is no significant difference between the compressive strength of $M_f$ and $M_s$
- $H_1$: $M_f$ has a better compressive strength than $M_s$

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<th>DOF</th>
<th>TSV</th>
<th>CV</th>
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**Table 3**

If the test statistic value lies within the rejection region, $H_0$ is rejected and $H_1$ is accepted, that is, $M_f$ has a higher compressive strength than $M_s$. 
Otherwise,

If the test statistic value lies within the acceptance region, then $H_0$ is accepted, hence, there is no significant difference between the compressive strength of $M_f$ and $M_s$.

The conclusion is highly dependent on the critical value. If the test statistic value is larger than the critical value, than the null hypothesis is rejected meaning that the value of the first sample is greater than the value of the second sample. In the case of Table 3 above, only one test resulted in an accepted null hypothesis by having a test statistic value of 1.12 which is considerably smaller than the critical value and lies within the acceptance region. The test statistic value is also highly dependent on the difference between the two sample means. The larger the difference, the larger the test statistic value will be. In this case, the largest difference between the two-sample means was between $M_2$ and $M_6$ resulting in the largest test statistic value.

**Independent Sample T-Test for 28-day Compressive Strength**

By forming the null and the alternative hypothesis:

$H_0$: There is no significant difference between the compressive strength of $M_f$ and $M_s$

$H_1$: $M_f$ has a better compressive strength than $M_s$

From Table 3 above, it was concluded that similar to the results at 7-days, the null hypothesis created to test $M_2$ against $M_3$ was accepted. In addition, the test between $M_1$ and $M_2$ also resulted in the null hypothesis to be accepted. This means that at 28 days, the mean compressive strength between $M_1$ and $M_2$ was significantly similar when compared to the compressive strength at 7 days. For the other three tests, the results were relatively similar to the results at 7 days, meaning that the null hypothesis was once again rejected for all three tests.

<table>
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<td>95%</td>
<td>10</td>
<td>21.69</td>
<td>1.812</td>
</tr>
</tbody>
</table>

**Table 4**

**Independent Sample T-Test for the Weight of the Samples**

By forming the null and the alternative hypothesis:

$H_0$: There is no significant difference between the mean weight of $M_f$ and $M_s$

$H_1$: The weight of $M_f$ is more than the weight of $M_s$

As can be observed in Table 4 above, the test statistic value for $M_2$ against $M_3$ was 0. This identifies that the mean weight of the two samples was equal. All the other tests identify that there was a significant difference in the weights of the two samples being tested. Having such a difference in weight resulted in a very high test statistic value which lies in the rejection region.
Regression Analysis

The regression analysis was used to assess the relationship between the dependent and independent variable being the compressive strength and the percentage of replacement respectively. Figure 4.9 explains the relationship between the compressive strength and the replacement percentage showing also the maximum and the minimum compressive strength. As can be observed from Figure 4.9 the regression equation obtained was:

\[ y = -1.1133x + 63.637 \]

Having a negative gradient identifies that as the percentage of plastic increases, the compressive strength of the final product decreases. By interpolation, replacing the fine aggregate by 48% will result in a compressive strength of approximately 10N/mm² meaning that such mixture cannot be utilised as a load-bearing structure but can be utilised for non-load bearing applications such as pavements. Still, this might not be true because at this stage it is difficult to conclude whether the result follows a linear trend or an exponential one.

![Regression Analysis](image)

**Figure 4.9: Regression analysis**

**Discussion on the Results Obtained**

**Compressive Strength**

As can be observed, the compressive strength of the concrete both at 7 days and 28 days kept on decreasing as the percentage of PC plastic increased. From the conclusion presented by Farooq et al. (2019), which stated that as the percentage of the plastic aggregate increased, the compressive strength decreased, the methodology used within this research confirms the following statement. Such results also agree with the conclusions presented by Hannawi et al. (2010) which stated that the increase in plastic resulted in a decrease in the overall compressive strength. The results obtained create a contradiction with the conclusions presented by Martinez et al. (2017) where it was stated that the introduction of polycarbonate plastic up to a certain percentage increased the compressive strength when compared to the control mixture.

Despite such relation, Farooq et al. (2019) also stated that the compressive strength of concrete increased when the cement was replaced by 10% silica fume. As can be identified
by the independent T-test and visually through the presented graphs, the obtained results do not fit with such a theory since the compressive strength when silica fume was introduced decreased both at 7 and 28 days. The obtained results were in line with the conclusions presented by Srivastava (2014) where the researcher stated that due to the replacement of the primary binder, which is cement, the compressive strength decreases.

**Final Weight of the Concrete Cubes**

As can be identified from Figure 4.7, as the percentage of plastic increased, the weight of the blocks decreased from 8.5kg to 7.69kg. Such a result agrees with the conclusion presented by Cassar (2019) where the researcher stated that the higher the percentage replaced, the lower the weight of the final product will be.

**Independent T-test**

The results obtained from the independent sample T-test which identified whether there was a significant difference between the mean compressive strength of a mixture, and another showed that at 7 days, there is a significant difference between the control mixture and the C25+10%SF mixture. However, at 28 days the results show that there is no significant difference in the compressive strength, which contradicts the results presented by Pradhan and Dutta (2013) where the researchers concluded that silica fume increases the compressive strength of concrete at both 7 days and 28 days.

From the T-test, it was also concluded that there is no difference in compressive strength between the C25+10%SF and C25+10%SF+5%PC mixtures both at 7 and 28 days. However, when compared to the C25+10%SF, all the other mixtures including plastic have a significantly lower compressive strength.

**One-Way ANOVA Test**

The ANOVA test was performed to determine whether there is a significant difference in compressive strength amongst all the six mixes for both 7- and 28-day testing. From the results obtained, it was concluded that there is a significant difference in the compressive strength between all mixes.

**Conclusion**

From the results obtained, through the methodology adopted for the purpose of this research, multiple conclusions were achieved. From the control mixture which did not include any additives to increase compressive strength, it was concluded that dolomite aggregate, which was imported, does affect the properties of concrete. With the use of imported aggregate, compressive strengths achieved were much higher than what was expected creating a variety of opportunities where such concrete can be implemented.

The second conclusion was that at a 10% partial replacement of cement with silica fume, the compressive strength did not exceed the traditional mixture. Although the independent sample t-test concluded that there was no significant difference between the two strengths, the addition of silica fume was expected to provide a greater strength to the final product.

Through such research, it was also concluded that although the strength decreased drastically when the 5% partial replacement of sand was exceeded, the 10%, 15% and 20% mixtures can still be utilized as a load-bearing structure. The compressive strengths of the 10% and 15% partially replaced mixtures were relatively the same, meaning that through such research previous replacement percentages have been exceeded.
Agreeing with previous studies, it was also concluded that although the mixture included different aggregates and the addition of silica fume, the final weight of the concrete blocks decreased as the plastic percentage increased.

Also satisfying the second aim of this research, by using a regression analysis, the researcher concluded that the maximum percentage of fine aggregate replacement with polycarbonate plastic particles where the concrete can still be utilized for non-load bearing structures was 48%. A mixture consisting of 48% polycarbonate plastic would be ideal for alternative structures such as pavements.

References


