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Scrutinizing the Effect of Water Temperature on the Compressive Strength of Recycled Concrete

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Abstract After demolishing rigid roads and old buildings, concrete is often rendered worthless and thrashed as waste. Currently, sustainable concrete construction is very popular, and the goal of the industry is to protect the population's well-being by reducing CO_2 emissions and encouraging the effective use of natural resources. One of the causes of decreased quality of recycled products is the adherence of cement paste to concrete demolition. Therefore, this study aims to examine the effect of water temperature on the compressive strength of recycled concrete. This is carried out with the hope that water temperature can impact the disintegration of the cement paste in the demolition concrete, thereby strengthening the bond between aggregates. The water temperature applied in this study was 25°C, 60°C, and 100°C, while the levels of recycled concrete aggregate (RCA) used were 25%, 50%, and 80%. The results showed that the highest compressive strength was obtained with an average of 26.23 MPa at a water temperature of 25°C and 25% RCA. However, this value is still below the composition of the natural aggregate, which is 28.6 MPa. Due to the rapid hydration caused by the high-water temperature, the process of forming concrete on the surface is accelerated while the interior remains weak. This situation affects the weakening of the compressive strength of concrete. Furthermore, this study shows that high water temperatures are beneficial for the cement paste decay process in recycled aggregates, but it is best to use a normal temperature of 25°C when mixing the water.

Keywords Water Temperature, Recycled Concrete, Sustainability, Compressive Strength

1. Introduction

Concrete is one of the most widely used construction materials, and its main ingredients in concrete mixes are cement, coarse and fine aggregate, water, and additives [1]. Although only as a filler, the fine and coarse aggregate proportions of the total concrete mixture are extremely high.

In the manufacture of concrete, water is the most important ingredient as a concrete adhesive which can affect the compressive strength and *setting time* of concrete. Other factors include aggregate type, water temperature in the mixture for making concrete, cement, and the characteristics of the material used. Furthermore, water temperature in the concrete mixture is an important factor because, at a high degree, it decreases the compressive strength of the concrete [2]. It also determines the impact of mixing water with concrete setting time [3]. Each location has a different water temperature both in the field and in the laboratory, where samples are taken before being applied to the field. The water temperature varies during the treatment process, as it mostly depends on the weather in the field.

Construction and demolition waste is currently a major concern due to the increasing amount of debris, lack of disposal sites, increased disposal costs, and transportation. Consequently, environmental deterioration is an issue, particularly concerning the amount of available natural aggregate, which may exacerbate the problems related to construction and demolition debris. Replacing natural aggregates with recycled aggregates affects the properties of concrete. Some of the effects include a decrease in the compressive strength of recycled aggregate concrete with a reduced density, an increase in water absorption capacity, and a decrease in the modulus of elasticity [4]. The use of recycled aggregate in concrete reduces the amount of primary raw materials and demolition debris. However, its use as a substitute for natural aggregates in concrete is not widely practiced.

The experimental results of a previous study [5] showed that the concrete samples of the recycled aggregate had good quality at ambient temperature. At a high temperature, it was considered to be quite close to concrete made with natural aggregates. Furthermore, [6] found that the effect of temperature on recycled coarse aggregate concrete resulted in an average decrease in strength of 55% across all mixes. According to [7], understanding and studying the behavior of concrete and its forming elements requires knowledge of the characteristics of each component, namely cement, fine and coarse aggregate, as well as water. Some basic properties of concrete include resistance to compressive stress and weakness to tensile stress.

2. Materials and Test Program

2.1. Material

2.1.1. Cement

Portland cement is produced by grinding slag, which mainly consists of hydraulic calcium silicate, with additional ingredients in the form of one or more crystals of calcium sulfate compounds and other additives. According to [8], cement and water are included in adhesives which undergo a chemical reaction to become a paste after mixing, stick together within a few hours, and harden in a few days.

Before obtaining the mix design, the characteristics of the cement should be tested for its density and setting time. *Le Catelier* tube and *Vicat* tool were used for the density and cement setting time test, respectively, as shown in Figures 1 and 2.

Figure 1. Test the density of cement using a Le Chatelier tube

Figure 2. Vicat apparatus

The hydration process occurs from outside when the cement is in direct contact with water. Gradually, these results precipitate on the exterior and the unhydrated cement core on the interior, leading to a tiny volume. After hydration, the resulting precipitate on the surface of the cement grains forces water to diffuse into the interior, which is not yet hydrated, causing the hydration process to be increasingly difficult, thereby slowing its rate. In this test, the cement setting time used was 105 minutes, as shown in figure 3.

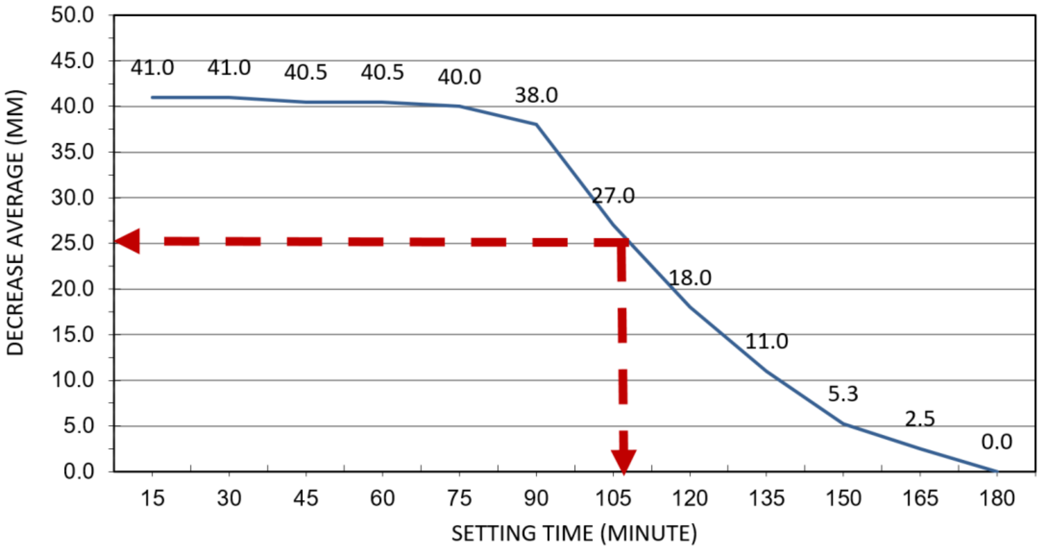

Figure 3. Graph of cement penetration consistency

Figure 4. Water preparation equipment according to the test temperature

2.1.2. Water

Water is one of the important factors in the manufacture of concrete. It reacts with cement to form an aggregate binding paste, affecting its compressive strength and the strength of the concrete itself. Furthermore, excess water will cause the concrete to bleed, meaning that the water and cement will move onto the surface of the freshly mixed concrete that has just been poured.

This study uses various water temperatures, including 25ºC, 60ºC, and 100ºC. Heating and temperature measurements were carried out using a stove and a thermometer, as shown in Figure 4.

2.1.3. Aggregates

Aggregate is a natural mineral grain that functions as a filler in mortar or concrete mixtures. It occupies approximately 70% of the mortar or concrete volume. Even though it is referred to as filler, aggregate significantly impacts the properties of mortar/concrete. Therefore, its selection is an important part of making mortar/concrete [9].

2.1.3.1. Coarse Aggregate

A coarse aggregate is a rock whose grain size is larger than 4.80 mm (4.75 mm). Coarse aggregate for concrete is in the form of gravel due to the disintegration of rocks or as crushed stoned from breaking rocks, with sizes ranging from 5 to 40 mm. The maximum permitted grain size depends on the intended use.

In this study, the natural coarse aggregate was obtained from Tanjungan, South Lampung, with a maximum size of 20 mm. Its collection process includes testing the characteristics of the coarse aggregate, one of which was the sieving test with the results as illustrated in Figure 5.

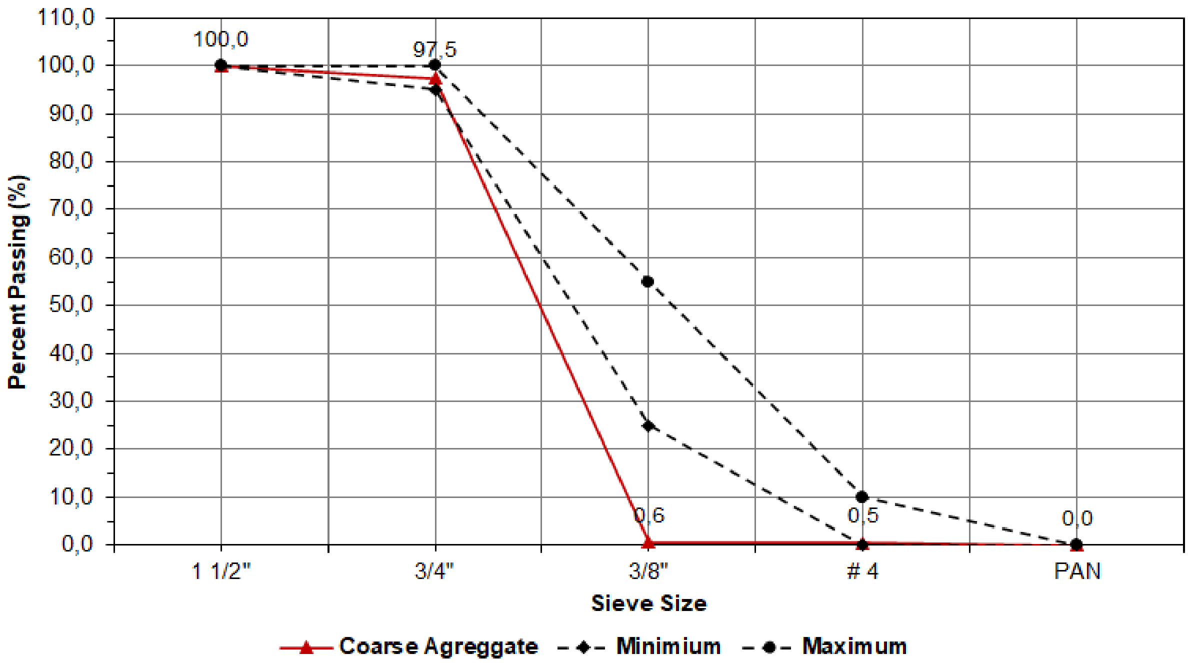

Figure 5. Coarse aggregate gradation curve with a maximum size of 20 mm

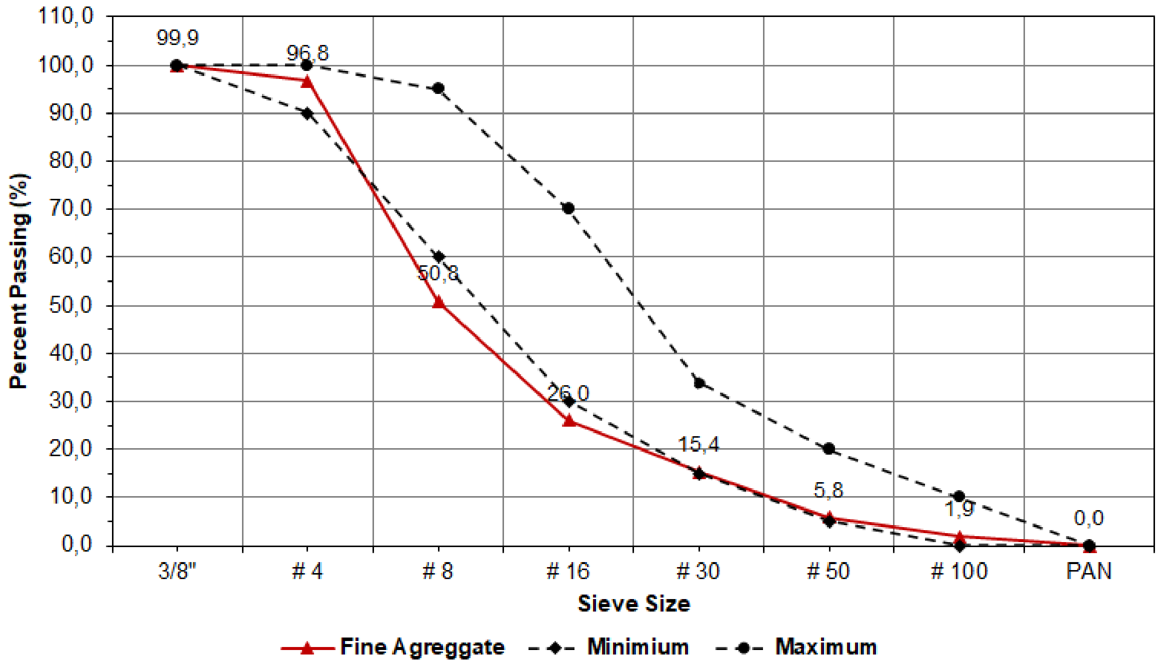

Figure 6. Fine aggregate gradation curve

2.1.3.2. Fine Aggregate

According to [10], fine aggregate consists of natural sand resulting from the disintegration of rock or sand produced by the stone-crushing industry, with the largest size of 4.8 mm.

The fine natural aggregate used in this study was obtained from Mount Sugih sand, Central Lampung, with gradation characteristics, as shown in Figure 6.

2.1.4. Recycled Concrete Aggregate (RCA)

Recycled concrete aggregate is crushed and reused in new concrete mixes. Recycled concrete from existing buildings such as roads, bridges, and other structures is crushed and manually or mechanically filtered to form concrete aggregates. In many regions, obtaining high-quality aggregates is becoming increasingly difficult due to upgrades and continuous awareness of environmental protection, and concrete recycling is becoming more important. This recycling can protect the environment and recover a new type of aggregate from parent concrete, which is derived from natural aggregates.

One way to conserve natural resources is by using recycled aggregate from construction and demolition waste, such as reducing landfills' demand and contributing to a sustainable built environment [11], [12]. Therefore, recycled concrete aggregates are an excellent alternative, and their use in *engineering* has received much attention in recent years [13]. The properties of RCA, such as specific gravity, absorption, and the number of contaminants present, contribute to the strength and durability of concrete. Furthermore, the quality of RCA itself depends on the features of the original aggregate as well as the condition of the crushed concrete [1]. The main difference between RCA and NA is the presence of mortar adhering to the surface of the RCA [14].

The RCA gradation test was carried out, and the results are shown in Figure 7. The gradation was improved by increasing the percentage of medium and small sizes.

2.2. Test Program

2.2.1. Mix Design Recycled Concrete

Due to the mortar adhering to the recycled aggregate, the volume of mortar in RCA is larger than the natural, while the aggregate volume is smaller. Furthermore, changes in the ratio of raw materials making up the concrete are responsible for the deterioration of the RCA properties. However, this can be controlled by the equal volume mortar mix design method, which considers the bond in RCA as mortar rather than aggregate [15].

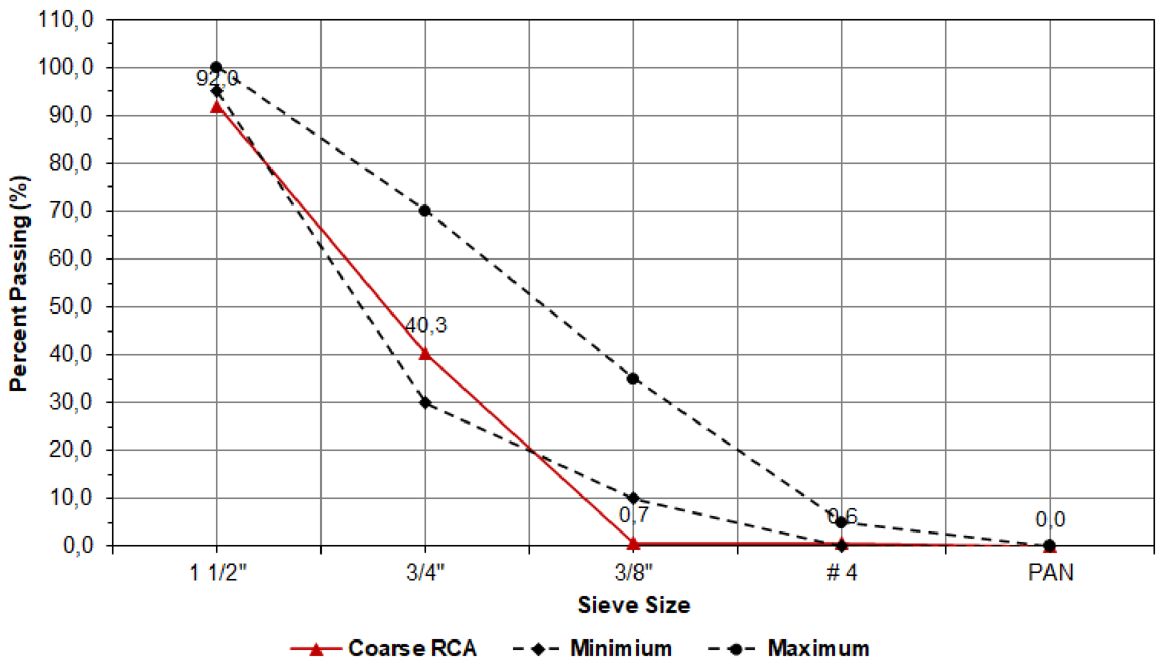

Figure 7. Coarse RCA gradation curve

Table 1. Fine aggregate characteristics

No	Type of Testing	Testing Method	Result	Unit
1	Fineness Modulus	SNI 2417:2008	5,034	%
2	Bulk Specific Gravity (SSD)	SNI 1969:2016	4,145	g/cm ³
3	Absorption	SNI 1969:2016	2,384	%
4	Water Content	SNI 1965:2019	4,249	%
5	Unit Weight	SNI 2417:2008	1582	Kg/m ³

Table 2. Coarse aggregate mix RCA characteristics

No	Type of Testing	Testing Method	Result	Unit
1	Fine Modulus	SNI 2417:2008	3,340	%
2	Maximum Nominal Size (mm)	SNI 7656:2012	37,5	mm
3	Bulk Specific Gravity (SSD)	SNI 1969:2016	2,471	g/cm ³
4	Absorption	SNI 1969:2016	1,024	%
5	Water Content	SNI 1965:2019	2,618	%
6	Unit Weight	SNI 2417:2008	1543	Kg/m ³

Table 3. Design of concrete mix composition

RCA content	Cement (kg)	Water (Litre)	Coarse RCA (kg)	Coarse NA (kg)	Fine NA (kg)
RCA 0%	2,388	1,087	0,00	5,076	3,886
RCA 20%	2,109	0,960	1,106	4,424	4,183
RCA 50%	2,109	0,960	2,822	2,822	4,068
RCA 80%	2,109	0,960	4,608	1,152	3,953

Mix design is the process of selecting the appropriate mix composition for the manufacture of concrete and determining the relative amount for economical production without compromising the minimum permissible criteria, such as design strength, *durability*, and consistency. Aggregate characteristics were tested based on the method of [16], with several tests, as shown in Tables 1 and 2.

This design aims to determine the proportions of concrete materials, namely cement, fine aggregate, coarse aggregate, and water, that meet the criteria for workability, strength, and durability, as well as completion by specifications. Furthermore, the proportion produced in this design must be optimal or use the minimum amount of materials possible, considering both technical and economic criteria. The design of concrete mixtures is complex when viewed from the differences in the properties and characteristics of the constituent materials. This study uses the method of [17] for designing concrete mixtures.

The mixing water temperature is added with variations of 25°C, 60°C, and 100°C. Ten test objects were made for each condition resulting in a total of 120 test objects. The results of this mixed design are shown in Table 3.

2.2.2. Slump Test

The slump test is carried out to determine the viscosity value of the concrete mix using a test tool called the Abraham cone. The *slump* value is used to measure the level of *workability* of a concrete mix, which affects concrete *workability*. A greater *slump* value indicates ease of work and vice versa [18].

The slum values used in this study range from 75 mm to 100 mm, as shown in Figure 8.

Figure 8. Testing the Slump Test

2.2.3. Compressive Strength Test

After experiencing the maintenance process of concrete by immersion in a pool of water, the test object was removed a day before testing, namely the 6th and 13th days. Compressive testing was then carried out with a universal testing machine, and the results are shown in Table 4.

A total of 120 objects were tested for compression at the age of 7 and 14 days, then the conversion was carried out at 28 days. The results show that concrete with natural aggregates at 25°C produces the highest compressive strength of 33.63 MPa. The test results are described with a bar graph in Figure 9.

Table 4. Compressive Strength Recycled Concrete (MPa)

Code	1	2	3	4	5	6	7	8	9	10
100ºC-80%	17,38	22,07	14,95	14,95	25,02	18,34	20,27	17,12	17,12	15,51
100ºC-50%	19,46	24,33	23,03	21,03	25,37	13,58	16,35	20,85	14,74	16,15
100ºC-20%	26,94	27,46	24,85	24,85	27,46	17,38	21,30	24,20	19,76	19,76
100ºC-0%	28,41	26,59	25,11	22,16	28,93	22,14	21,82	24,78	25,81	21,11
60ºC-80%	25,63	19,72	25,55	24,33	22,85	20,01	18,73	14,29	15,32	16,92
60ºC-50%	23,72	24,94	22,07	22,07	21,72	19,76	18,15	22,78	19,82	19,95
60ºC-20%	20,59	21,72	19,03	19,12	19,03	19,82	16,99	16,92	18,28	19,76
60ºC-0%	26,94	26,24	26,59	28,24	30,50	15,51	22,72	20,66	22,27	20,66
25ºC-80%	24,76	25,46	21,81	24,94	27,37	21,43	17,89	22,39	20,79	20,14
25ºC-50%	23,55	24,33	27,28	26,76	24,76	21,88	19,11	19,95	20,79	19,11
25ºC-20%	31,98	27,98	28,76	30,59	22,94	25,10	25,29	23,55	23,23	22,85
25ºC-0%	32,15	27,37	31,89	33,63	35,10	23,30	24,71	24,26	25,42	24,78

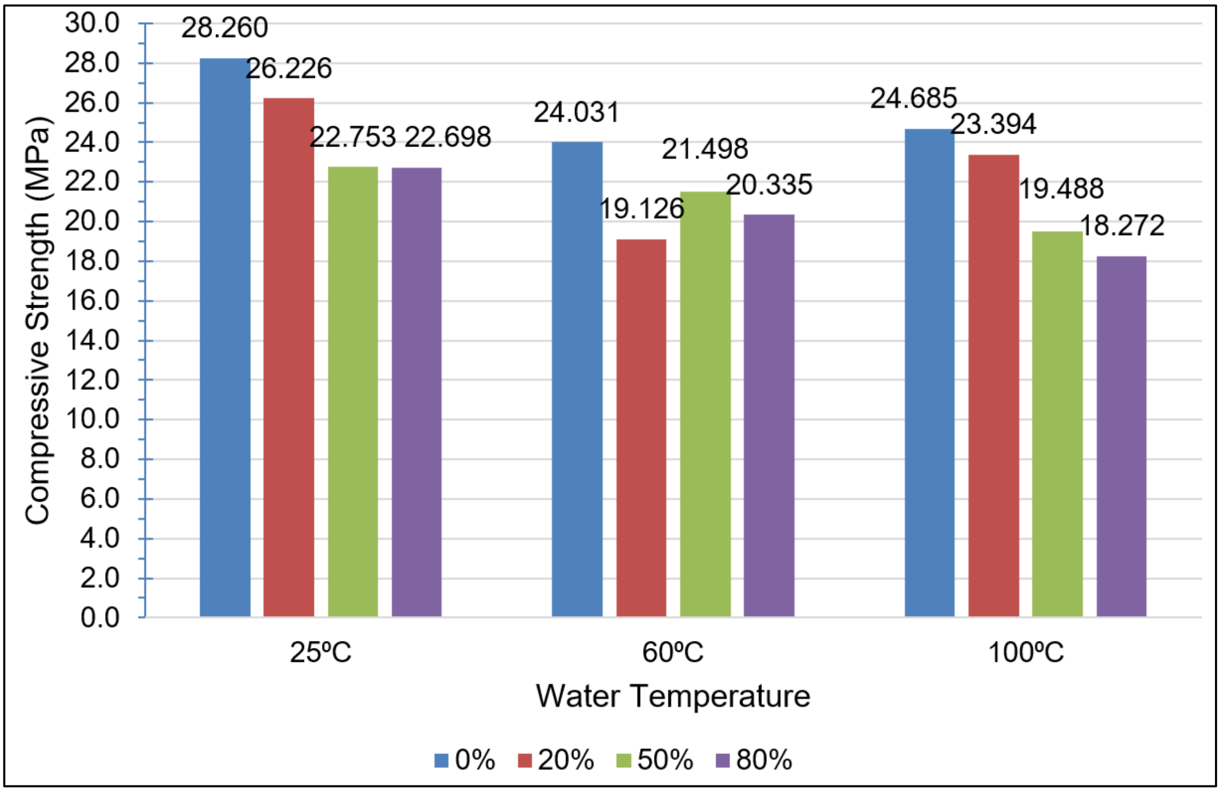

Figure 9. Graph of recycled concrete compressive test results

3. Result and Discussion

3.1. Data Analysis

3.1.1. Normality test

The normality test determines whether the data used is normally distributed [19]. In this study, the Minitab version 19.1 program was used as a tool for data analysis. The data were tested based on the Kolmogorov-Smirnov principle, as shown in Figures 10 and 11. The variable is declared normal with the analysis results of KS = 0.062 and P-Value> 0.015.

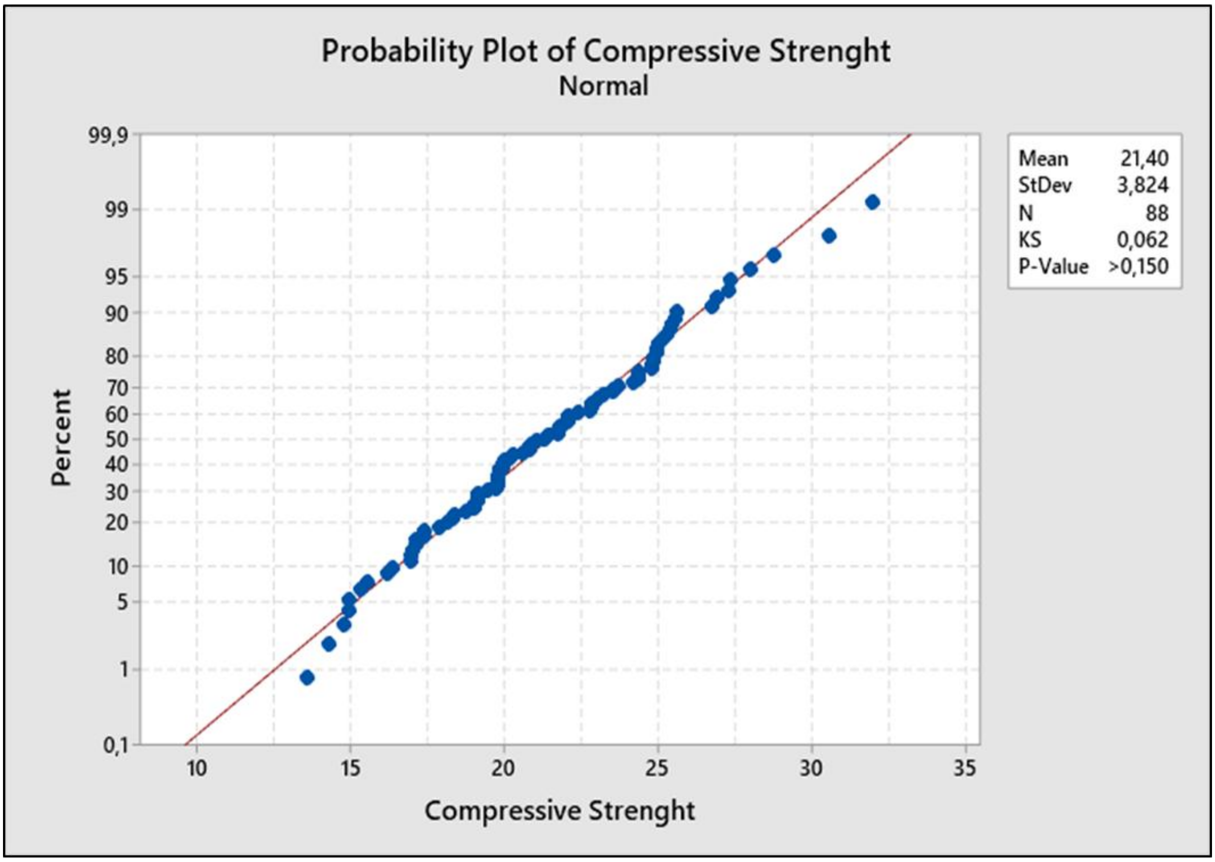

Figure 10. Graph of Normality Test

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	271,87	135,93	13,45	0,000
RCA	2	66,95	33,48	3,31	0,042
Temperature*RCA	4	125,56	31,39	3,10	0,020
Error	79	798,67	10,11		
Total	87	1271,91			

Figure 11. Results of normality test data analysis

3.2. Completely Randomized Design (CRD)

A completely randomized design (CRD) is a field design at a homogeneous location. This design is considered to be random because each experimental unit has an equal chance of receiving the treatment, and it is complete because all treatments intended for the experiment are implemented [20].

The linear model for CRD consisting of t treatments and r_i replications is as follows [21]:

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} : i = 1,2,3,\ldots t \quad j=1,2,3,\ldots,r_i \qquad (1)$$

Where:
Yij = observations on the i treatment in the j repetition
μ = general average
τI = treatment i
εij = error component

Furthermore, the analysis was assisted using the Minitab 19.1 program, with the results as shown in Figures 12, 13, and 14.

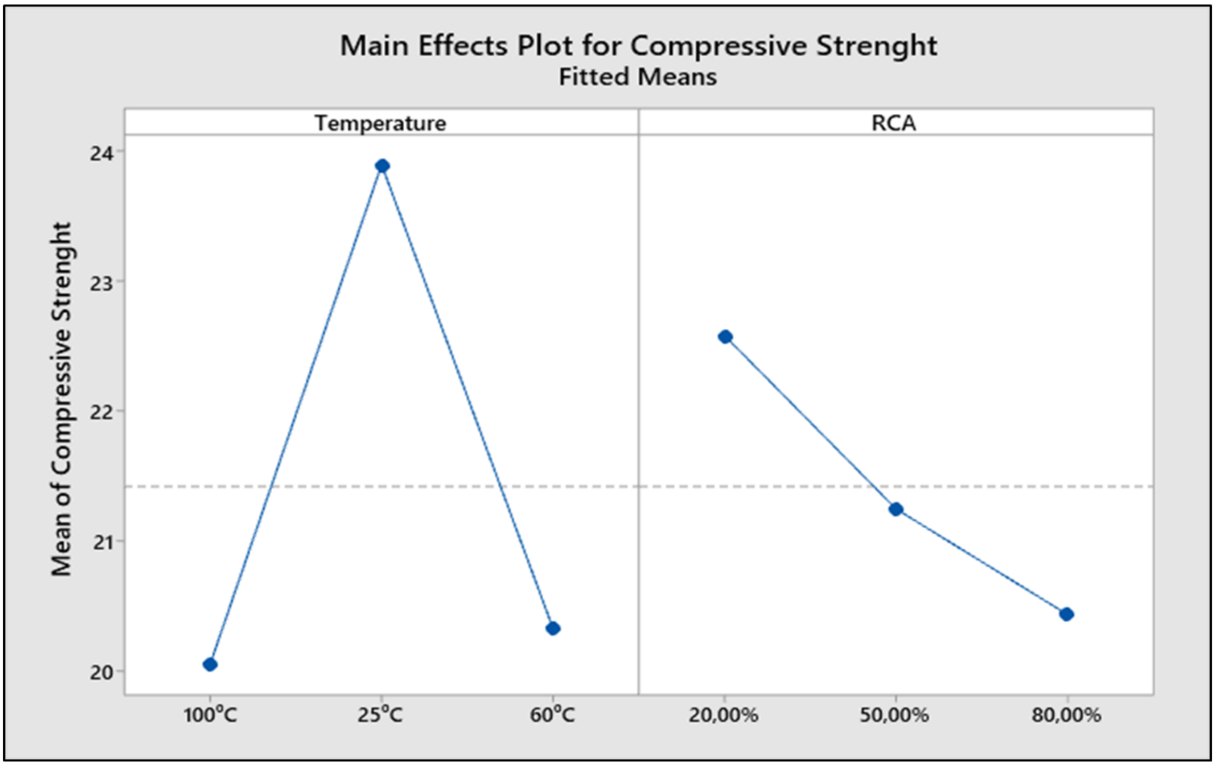

Figure 12. Effect of Temperature and RCA Levels

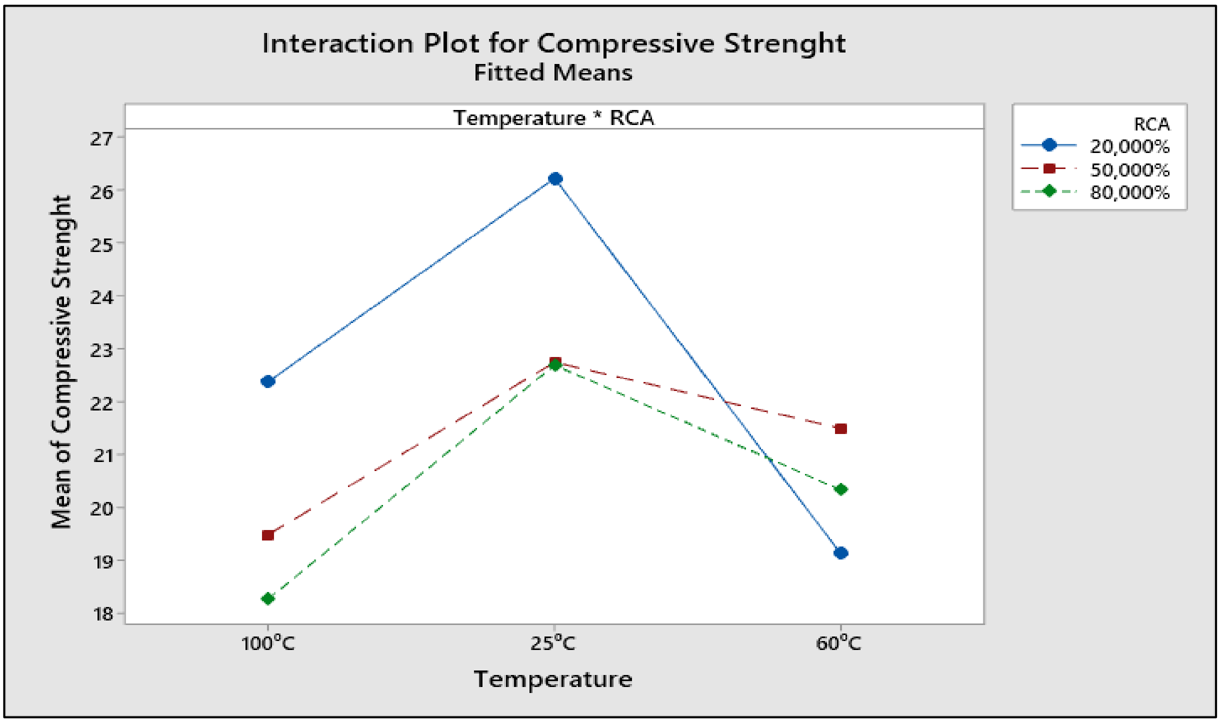

Figure 13. Interaction of influence between variables

Tukey Pairwise Comparisons: Temperature

Grouping Information Using the Tukey Method and 95% Confidence

Temperature	N	Mean	Grouping	
25°C	30	23,8922	A	
60°C	30	20,3195		B
100°C	28	20,0458		B

Means that do not share a letter are significantly different.

Figure 14. Tukey analysis results and the effect of temperature and RCA levels

The ANOVA result of a CRD shows that the P-Value for the temperature and RCA factors is 0.000 and 0.042<0.05, respectively, and 0.020<0.05 for the combined factors. Therefore, it can be concluded that these three factors influence each other.

The Tukey's advanced test, which compares compressive strength with temperature, as shown in Figure 13, and with *RCA* in Figure 14 using a 95% confidence level, indicates that 60ºC and 100ºC temperatures have the same effect on compressive strength.

4. Conclusions

The use of high water temperature for making concrete has no significant effect on dissolving the cement paste attached to the RCA coarse aggregate. However, high water temperatures affect the hydration and setting time of concrete. A higher water temperature decreases the compressive strength of the concrete. This is due to hydration that is too high during the setting time, which results in fine cracks in the resulting concrete.

After treatment and test with the addition of 20% RCA, the result shows that a water temperature of 25ºC produces the largest compressive strength of concrete, which is equal to 28.260 MPa. The value is determined by the average age of concrete, which is 28 days based on the conversion of aged concrete, 7 and 14 days. Therefore, this experiment reportedly achieved the planned concrete strength of 25 MPa.

It is hoped this the research can be the first step in using recycled concrete as an alternative solution to conserving natural resources, especially natural aggregates which will run out over time. Furthermore, the authors suggest that this research should be improved by changing the function of high-temperature water as a loosening of cement paste bonds first before mixing new aggregates and cement. This can reduce the hydration process that is too fast due to the high temperature of the mixing water. Thus it will produce recycled concrete that is stronger than the process carried out in this study.

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