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*Research article*

# Heat resistance of lightweight concrete with plastic aggregate from PET (polyethylene terephthalate)-mineral filler

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**Abstract:** The addition of filler to plastic aggregate results in better mechanical characteristics of concrete than concrete with plastic aggregate without filler; this has been proven in various studies that have been conducted. Different types of minerals have been used as fillers; namely, red sand, fly ash, rice husk ash, and cement. The use of plastic aggregate in concrete as a substitute for natural aggregate indicates that the concrete produced is included in the lightweight concrete category. It is interesting to examine the effect of heat on the mechanical characteristics of this concrete. This study will use two types of plastic aggregate which are differentiated based on the filler used. The first aggregate is an artificial aggregate made from PET plastic with rice husk ash filler; the second aggregate uses Portland pozzolana cement. Four proportions of the concrete mixture were made using these two types of plastic aggregate. As a reference, a fifth concrete type is created, namely concrete with all-natural aggregate fractions. The test results show that starting at 100 °C the concrete with plastic aggregate begins to fine cracks which can only be seen using a digital microscope. While in reference, concrete cracks began to appear at 200 °C. The presence of cracks causes the mechanical characteristics of the concrete to decrease significantly. On heating of 300 °C and 400 °C, the specimens with plastic aggregate appear charred, and there are holes due to the PET decomposition process, and more cracks with large gaps.

**Keywords:** lightweight concrete; plastic aggregate; synthetic aggregates; mineral filler; PET plastic waste; heat resistance

## 1. Introduction

Bottled drinking water is made based on the basic human need for drinking water that is easy to obtain, practical, clean, and healthy. Plastic was chosen as the packaging with its advantages, namely lightness, cheapness, comfortable shape, and recyclable. In its development, the demand for bottled water has increased from time to time. One million plastic bottles of bottled drinking water or soft drinks worldwide are sold to consumers every minute and increase by 20% by 2021 [1]. The increase will result in a figure of about 20000 bottles being purchased by consumers every second. In 2016 as many as 480 billion plastic bottles were sold worldwide, and this figure will be 583.3 billion in 2021. Meanwhile, Indonesia is the fourth largest plastic bottle producing country, with 4.82 billion bottles per year [2]. Weak waste management causes plastic bottle waste to be thrown away at final disposal or reaches the sea and threatens all marine animal life in it.

Generally, plastic bottles are made from highly recyclable polyethylene terephthalate (PET) type plastic. With a high, increasing number of products and single-use only, efforts to recycle are lagging. A material specialist who can find such materials must avoid single-use (and soon to be waste) products that do not decompose in nature. Simultaneously, ideas are also needed to reuse plastic waste that already exists (and with an increasing use) into useful materials.

Researchers in various parts of the world have reused PET plastic waste for building materials [3–11]. Mansour et al. [9] used original PET plastic bottles which functioned as a replacement for partition walls from traditional concrete blocks. Each PET plastic bottle is filled with dry sand, saturated sand, or filling only air, then stacked and bound using cement mortar. Each PET plastic bottle filled with dry sand, saturated sand, or no filling (air only), then assembled and bound using cement mortar. The results of his research show that the construction of plastic bottles filled with air can make one-story buildings with roof plates and has better thermal insulation than traditional concrete blocks. Another study uses recycled plastic waste from PET type mineral water bottles as coarse aggregate in concrete, while fine aggregate uses natural sand [3]. The research was conducted in several conclusions which are shown below. Concrete mixtures without chemical additives indicate that the compressive strength and tensile strength of the concrete are meager, namely 12 MPa and 1 MPa, respectively, due to the low adhesion strength between plastic aggregate and cement mortar. In the next stage, determining the maximum plastic aggregate size is 10 mm; the maximum cement water factor is 0.35 and using chemical admixture to adjust workability, showing that the strength of the concrete produced is up to 20 MPa. A similar study was carried out by making concrete mixtures with various W/C ratios, both for light aggregates and natural aggregates [5]. The results showed that PET aggregate with adequate granulometry produced suitable quality mixtures with lower concrete density (68.88%) but with similar mechanical characteristics to natural concrete. At low W/C ratios (with a cement content of 300 kg/m$^3$ or more), the mechanical strength of the concrete is determined by the coarse aggregate characteristics. In contrast, at high W/C ratios, the characteristics of the cement paste are decisive.

Apart from being a substitute for coarse aggregate, the use of fine aggregate from PET plastic flakes as a substitute for fine natural aggregate has been carried out [12,13]. The results show that the compressive strength, split tensile strength, and flexural tensile strength will increase at replacement levels up to 10%. More than this level, the mechanical characteristics of the concrete will decrease drastically. Research [13] also shows that the concrete modulus of elasticity will be smaller when using fine plastic aggregate—the more the percentage, the more significant the decrease in the elastic modulus value.

Another benefit that can be used from the properties possessed by PET plastic is its tensile strength capacity, which is quite large, which varies from 263.72 to 550 MPa [14]. Plastic filaments extruded from PET plastic flakes were made which functioned as reinforcing fibers in the concrete mixture. The results show that at 1% fiber content (to cement volume), PET with high tensile strength (550 MPa) has the most favorable compressive strength and tensile strength when the W/C ratio is high (0.53). Meanwhile, PET with low tensile strength has the best compressive strength and tensile strength when the W/C ratio is low (0.38). The paper also states that studies using PET fiber as reinforcement indicate that the energy absorption capacity increases in the range from 400% to 700% compared to concrete without PET fibers, making it possible to use it for earthquake-resistant structures.

Other types of plastic besides PET have been carried out such as the use of E plastic, namely plastic that comes from the waste of used electrical or electronic devices such as used monitor tube wrappers [15]. The use of expanded polystyrene foam (EPS) plastic or better known as styrofoam [16–18], plastic types of polypropylene (PP) [19], plastic types of high-density polyethylene (HDPE) [20,21], plastic types of polyethylene (PE) and polyvinylchloride (PVC) [22], and even the use of used tires [23].

The use of plastic materials in concrete will reduce the strength of the concrete. One of the reasons is because the density of the concrete is also reduced. To overcome this, Kaseem et al. [24] suggest replacing cement with fly ash from 10% to 30%. His research showed that the 30% cement replacement was able to achieve the highest compressive strength, namely 21.28 MPa. This research also concluded that plastics could be used to develop low-strength concrete structures. Another disadvantage of using plastic aggregate in concrete, either original or through further processing, is that it cannot absorb water, causing weak bonds between plastic aggregate and mortar. This weakness can be explained below, namely that water that cannot be absorbed in the mortar-aggregate interface will increase the W/C value, thereby reducing the concrete's quality in that zone. Also, plastic aggregates generally have a smooth surface which causes the friction stress capacity between the mortar-aggregates too low. Therefore, the interface zone of mortar-aggregate in concrete with plastic aggregate is a weak part of the binder-filler bonding system. To reduce these drawbacks researchers modified the water absorbency, surface roughness of plastic aggregates, or both [11,25–29].

Rumšys et al. [25] succeeded in grinding the plastic aggregate surface mechanically by mixing the plastic aggregate with sand in a mixer and rotating it for 5 minutes so that the plastic aggregate's surface became a lot of scratches. However, the results showed that the surface roughness that occurred did not affect the strength of the concrete or water absorption. Another attempt to improve the plastic aggregate surface was carried out by coating plastic aggregate from PET bottles with ground granulated blast-furnace slag (GBFS) [26]. The results showed that the GBFS layer reacts with calcium hydroxide to form C–S–H bonds, strengthening the plastic aggregate surface. Volcanic sand was chosen to coat polypropylene (PP) plastic aggregate [27]. Results showed that the coating was able to increase the compressive strength of concrete compared to concrete with aggregates without sand coating.

Another modification to improve water absorption or increase the surface roughness of plastic aggregates is done by adding filler to the hot plastic melt during the aggregate manufacturing process [11,29,30]. Fly ash with a carbon content of 12% is used as a filler mixed with HDPE type plastics to make artificial coarse aggregate [29]. Three types of coarse aggregate were prepared based on different proportions of filler-HDPE. Furthermore, using fine aggregate from natural sand, five types of concrete are made based on the proportions of different materials. The results show that the mechanical characteristics and cracking properties of the concrete improve along with the fly ash content in the aggregate. Meanwhile, Alqahtani et al. [30] using various types of fillers, namely: red sand, fly ash, and quarry fines, while the plastic waste used is of the type LLDPE (linear low density polyethylene).

Wiswamitra et al. [11] compared the use of various minerals, namely fine sand, fly ash, rice husk ash, and Portland pozolan cement as fillers in the manufacture of synthetic aggregates (plastic aggregates) with PET plastic bottle waste materials. Different types of plastic aggregate are made based on different proportions of filler-PET. In the early stages of his research, the plastic coarse aggregate that had been made was used to replace the natural coarse aggregate. The results show that a higher compressive strength of concrete is shown in almost all types of fillers used, this is when compared to reference concrete (concrete with plastic aggregate without filler). Synthetic aggregate with a proportion of 1 rice husk ash:5 PET; and synthetic aggregates with a proportion of 1 cement:3 PET; produces a high compressive strength of concrete and falls within the criteria for structural lightweight concrete.

The use of plastic as a material in concrete always raises curiosity about its resistance to heating. Various studies of heat resistance of concrete with plastic materials have been carried out. Koide et al. [3] concluded that the concrete with coarse aggregate of PET plastic has heat resistance up to 60 °C. Correia et al. [31] concluded in their research that during heating, the maximum temperature was higher for concrete with a plastic content than for concrete with natural aggregates. Meanwhile, the decrease in compressive strength, modulus of elasticity, and split tensile strength in concrete with plastic content is higher than that of reference concrete.

This study will test the mechanical characteristics of lightweight concrete after heating, then compare it with reference concrete, namely concrete without heat treatment. The synthetic aggregate used is a PET plastic filler mixed aggregate divided into two types of aggregate based on the filler used, namely rice husk ash and Portland pozzolana cement. This synthetic aggregate uses proportions and preparation methods following the research of Wiswamitra et al. [11].

## 2. Materials and methods

### *2.1. Materials*

The cement used is Portland pozzolanic cement (PPC) with a specific gravity of 3.15, with specifications that meet Indonesian standards, SNI 15-0302-2004 [32].

Fine aggregate uses local sand obtained from dunes with a specific gravity of 2.14 and a Fineness Modulus (FM) of 2.68 with a gradation that meets the Zone 2 fine aggregate gradations according to the grading limits for fine aggregates listed in the Indonesian national standard, SNI 03-2834-2000 [33] (Table 1).

**Table 1.** Grading limits of fine aggregates, SNI 03-2834-2000 [33].

| Opening size of sieve (mm) | Percentage by weight | | | |
|---|---|---|---|---|
| | Grading zone 1 | Grading zone 2 | Grading zone 3 | Grading zone 4 |
| 10.00 | 100 | 100 | 100 | 100 |
| 4.80 | 90–100 | 90–100 | 90–100 | 95–100 |
| 2.36 | 60–95 | 75–100 | 85–100 | 95–100 |
| 1.18 | 30–70 | 55–90 | 75–100 | 90–100 |
| 0.60 | 15–34 | 35–59 | 60–79 | 80–100 |
| 0.30 | 5–20 | 8–30 | 12–40 | 15–50 |
| 0.15 | 0–10 | 0–10 | 0–10 | 0–15 |

Natural coarse aggregate using local gravel with a specific gravity of 2.68 with a size passing through sieve No. 3/8" (with size of sieve hole = 9.5 mm), stuck in sieve No. 4 (with the size of the sieve hole = 4.76 mm), and has an FM value of 6.00

For the manufacture of artificial aggregate, the material used is plastic type PET (Polyethylene Terephthalate) without color from the packaging of beverage bottles in chopped form (Figure 1a), then the PET plate chopped is washed to remove impurities due to dirt or glue that may still stick, and finally dried in the sun. PET plastic has a specific gravity of 1.307, and a melting point of around 260 °C. This study made two types of artificial aggregate based on the type of filler mixed. The first filler is rice husk ash (Figure 1b) with a specific gravity of 2.73 which was previously sieved using sieve No. 16 (sieve hole size = 1.19 mm). The second filler is Portland pozzolana cement (Figure 1c) with a specific gravity of 3.15.

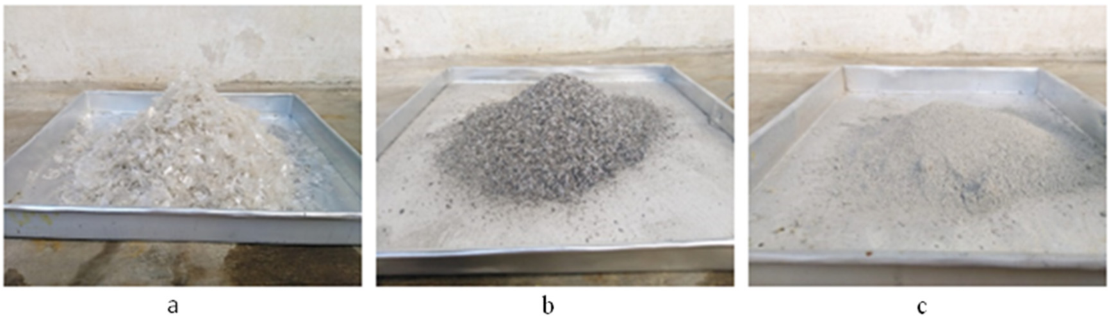

**Figure 1.** Artificial aggregate materials: (a) chopped PET plastics, (b) rice husk ash (as filler), and (c) Portland pozzolana cement (as filler).

*2.2. Methods*

This research was conducted in three stages (Figure 2), namely the manufacture of plastic aggregates, casting of concrete specimens, and testing of mechanical characteristics which are described in more detail in the following section.

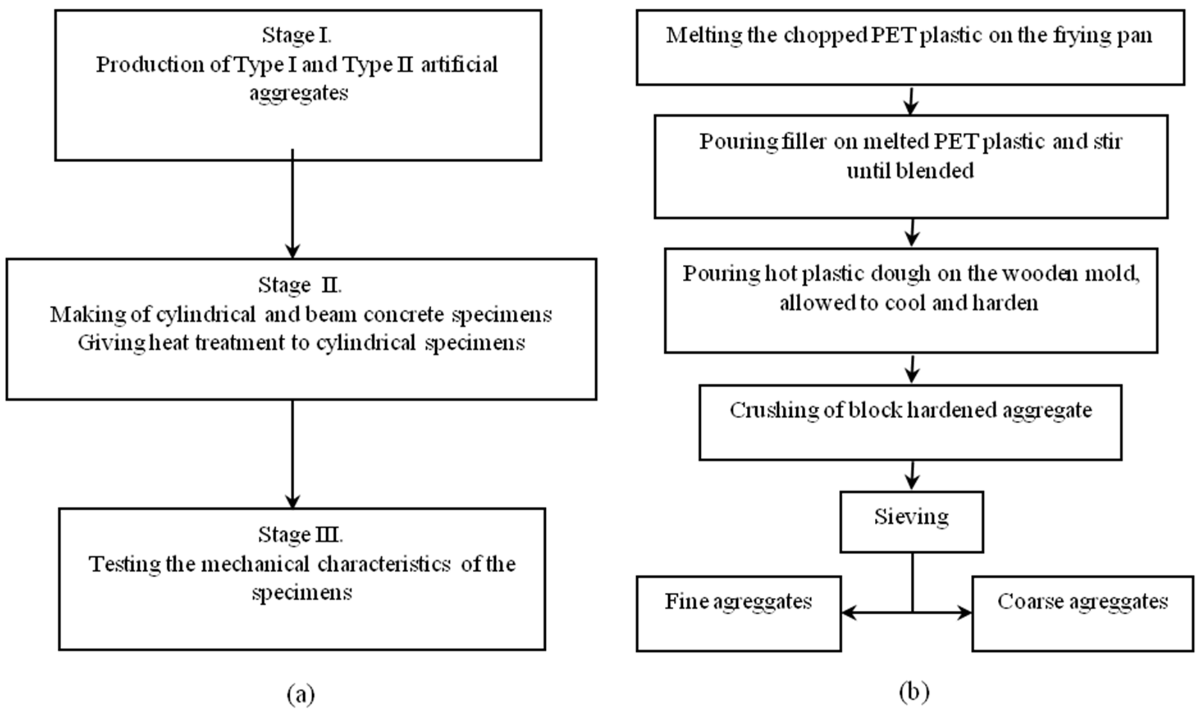


**Figure 2.** (a) The stages of research and (b) the sequence of making artificial aggregates.

### 2.2.1. Stage I—production of type I (PA I) and type II (PA II) plastic aggregates

The plastic aggregates are made like the flow chart shown in Figure 2b or in the sequence in Figure 3, with the first step being to melt the chopped PET plastic in a pan until all the plastic parts are melted. After the whole PET plastic becomes thick melt, then the filler powder (rice husk ash or cement) is poured into the pan, and the mixture is stirred again until the filler is evenly mixed. Then, the hot mix of the PET-filler mixture is poured into a wooden box mold and allowed to cool and harden. The hardened plastic block is then broken down using a hammer to make it smaller and put in the crusher. The resulting crusher fractions are then sieved to obtain fine and coarse aggregate fractions. This synthetic aggregate production follows the method of Wiswamitra et al. [11], which used filler of rice husk ash and Portland pozzolana cement. The ratio (weight ratio) of filler: PET plastic, namely one rice husk ash: five PET to produce plastic aggregate type I (PA I) and one cement: three PET to create type II plastic aggregate (PA II). Digital Microscope from Cooling Tech (Figure 4a) and Scanning Electron Microscope from Tabletop Microscope TM3030Plus (Figure 4c) was used to determine the microstructure synthetic aggregates, before and after heating.

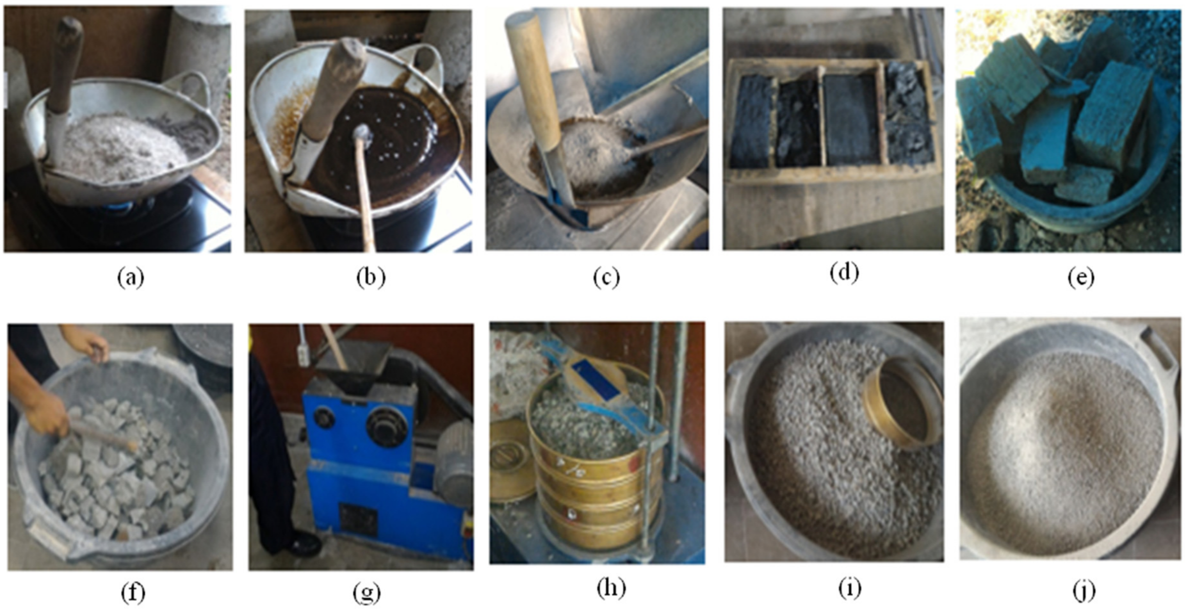


**Figure 3.** Artificial aggregate manufacturing process. (a) Chopped PET plastic on frying pan, (b) PET melts on the pan, (c) adding filler, (d) hot dough in a wooden mold, (e) harden PET-filler block, (f) hammering the block, (g) put into a crusher, (h) sifting, (i) coarse fraction aggregates, and (j) fine fraction aggregates.

### 2.2.2. Stage II—casting concrete specimens

At this stage, the two types of plastic aggregate that have been made (both coarse and fine) are used to create lightweight concrete. Five types of concrete are made. The first is concrete with fine natural aggregate and coarse aggregate from plastic aggregate type I/PA I (rice husk ash aggregate-PET), the second is concrete with both aggregate fractions (fine and coarse) is PA I, the third is concrete with fine natural aggregate and coarse aggregate from plastic aggregate type II/PA II (cement-PET aggregate), the fourth is concrete with both aggregate fractions (fine and coarse) is PA II. The fifth is reference concrete, namely concrete with natural aggregate. To simplify the mention of concrete types, Table 2 shows the name for each concrete mixture, the artificial aggregate's name, and the proportion of the synthetic aggregate constituent. The test specimens are cylinders with a diameter of 10 cm and a height of 20 cm used for testing the compressive strength and tensile strength of the concrete; beam size 10 cm × 10 cm × 40 cm for flexural tensile testing. Provide different temperature treatments; various specimens are put in ovens with varying temperatures, namely 100 °C, 200 °C, 300 °C, and 400 °C with a heating time of 2 h. One treatment as a reference is a concrete cylinder without heating. The oven equipment is shown in Figure 4b. Cylindrical specimens that do not undergo heating are assumed to receive a room temperature of 30 °C by the average temperature of one day at the research location. In Table 3, it can be seen the types of tests carried out, the kinds of temperature treatments, and the shape of the test specimens. The flexural tensile strength test is only carried out on samples without heating considering that the oven space capacity is insufficient to accommodate the specimen beam. Treatment of the concrete after casting is done by immersing all specimens in clean water for 14 d, then leaving the samples in open space until the samples are 28 d old and ready to be tested.

**Table 2**. ID name for each concrete, short name of the type of artificial aggregate, and proportion of the artificial aggregate constituent.

| No. | Concrete mix name | Fine aggregate | | Coarse aggregate | |
|---|---|---|---|---|---|
| | | Type | Filler-PET proportion | Type | Filler-PET proportion |
| 1. | FC-N | Natural sand | - | Natural gravel | - |
| 2. | FN-CPRha | Natural sand | - | PA I | 1 rice husk ash:5 PET |
| 3. | FN-CPCm | Natural sand | - | PA II | 1 cement:3 PET |
| 4. | FC-PRha | PA I | 1 rice husk ash:5 PET | PA I | 1 rice husk ash:5 PET |
| 5. | FC-PCm | PA II | 1 cement:3 PET | PA II | 1 cement:3 PET |

**Note**: FC-N = Fine & coarse → Natural; FN-CPRha = Fine → natural, Coarse → PET-Rice hush ash; FN-CPCm = Fine → natural, Coarse → PET-Portland cement; FC-PRha = Fine & coarse → PET-Rice hush ash; FC-PCm = Fine & coarse → PET-Portland cement; PA = Plastic aggregates.

**Table 3**. Type of test, heat treatment temperature, and shape of specimen

| Mechanical characteristics test | Temperatures treatment (°C) | Specimen shape |
|---|---|---|
| Compression test, splitting tensile test | 30; 100; 200; 300; 400 | Cylinder of 100 mm diameter × 200 mm height |
| Flexural tensile test | 30 (room temperature) | Beam of 100 mm × 100 mm × 400 mm |

(a) (b) (c)

**Figure 4.** Other equipment. (a) Cooling Tech digital microscope, (b) oven, and (c) Tabletop Microscope TM3030Plus.

### 2.2.3. Testing the mechanical characteristics of lightweight concrete

Several preparations were made before implementing the mechanical characteristic testing, including the application of sulfur capping to the cylindrical specimen and weighing the test object. Concrete compressive strength testing refers to Indonesian regulatory standards, SNI 03-1974-1990 [34]. The concrete compressive strength test set up is shown in Figure 5a. The split tensile strength test refers to the Indonesian national standard, SNI 03-2491-2002 [35], with the test set up shown in Figure 5b. The flexural tensile strength test is conducted as in Figure 5c.

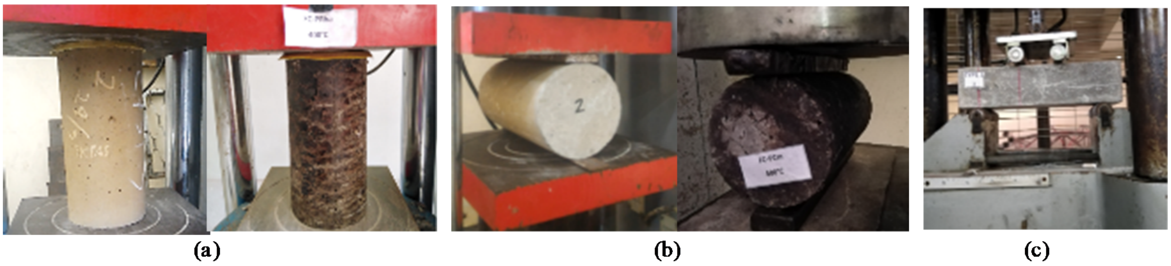


**Figure 5.** Testing of specimens (a) compression test, (b) splitting tensile test, and (c) flexural tensile test.

## 3. Results and discussion

### *3.1. Stage I—production of type I (PA I) and type II (PA II) plastic aggregates*

Two types of plastic aggregate produced at this stage, namely type I (PA I) and type II (PA II), consisting of fine and coarse fractions, as shown in Figure 6. Figure 7 shows the maximum magnification of the surface or edge of each synthetic aggregate using a Cooling Tech digital microscope with a magnication ratio of 40× to 1000×. The picture shows PA I synthetic coarse aggregate has a surface texture that is rougher and more porous than PA II. The gradation of fine aggregate of these two types of synthetic aggregates is made the same as the gradation of natural sand used for reference concrete, namely zone 2 for fine aggregate. Likewise, the synthetic coarse aggregate size is made the same as the natural coarse aggregate gradation, which passes through sieve No. 3/8" (with sieve hole size = 9.5 mm), stuck in sieve No. 4 (with sieve hole size = 4.76 mm). In Table 4, we can see the results of testing the characteristics of natural aggregate and artificial aggregate, where the addition of rice husk ash filler to PET plastic aggregate with a ratio of 1:5 makes the absorption of synthetic aggregate up to 2.43%, while aggregate with cement filler, the aggregate absorption only reaches 1.01%.


**Figure 6.** Filler-PET synthetic aggregates. (a) Fine plastic aggregate type I, (b) fine PA II, (c) natural coarse, (d) coarse PA I, and (e) coarse PA II.

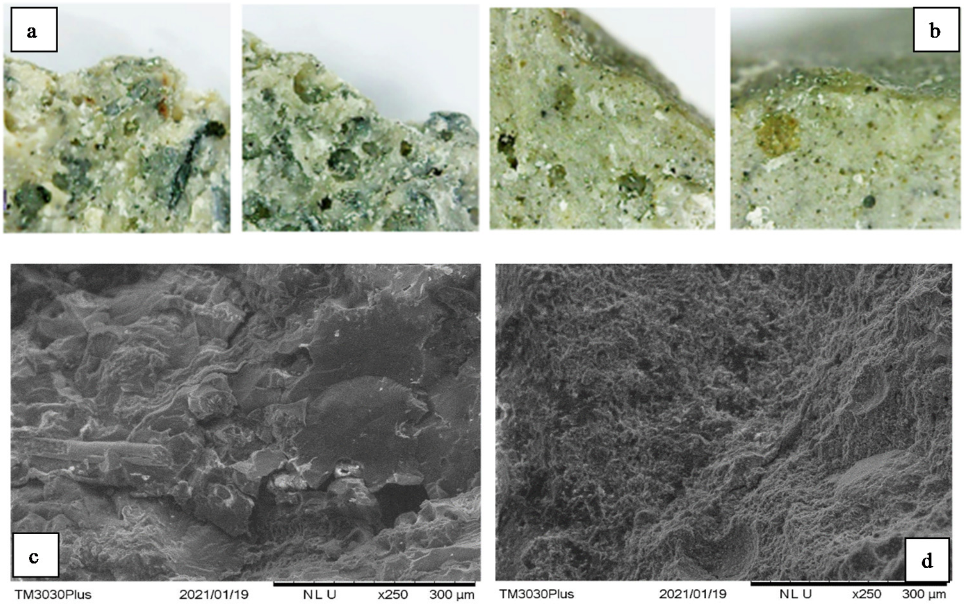


**Figure 7.** Surface texture and edges of plastic aggregates viewed using a Cooling Tech digital (a) and (b), and viewed using SEM (c) and (d). (a) PA I (rice husk ash-PET aggregate, (b) PA II (cement-PET aggregate), (c) PA I, (d) PA II.

**Table 4.** Characteristics of natural and synthetic aggregates.

| Parameter | Material type | | | | | |
|---|---|---|---|---|---|---|
| | Natural sand | Natural coarse | Fine PA I | Fine PA II | Coarse PA I | Coarse PA II |
| Specific gravity | 2.14 | 2.68 | 1.50 | 1.55 | 1.37 | 1.57 |
| Fineness modulus | 2.68 | 6.00 | 2.68 | 2.68 | 6.00 | 6.00 |
| Bulk density (kg/m$^3$) | 1305.87 | 1372.10 | 801.04 | 884.80 | 669.70 | 783.63 |
| Absorption (%) | 1.78 | 1.72 | 2.58 | 1.27 | 2.43 | 1.01 |

### *3.2. Stage II—Casting concrete specimens*

At this stage, a cylindrical specimen is produced with a diameter of 10 cm with a height of 20 cm and a concrete block measuring 10 cm × 10 cm × 40 cm. The consistency of fresh concrete for all types of concrete is carried out by adjusting the amount of water so that every concrete has a slump value that is not much different. All kinds of concrete have a slump value range from 45 to 6 mm. Table 5 shows the composition of the concrete mixture and the slump value for each type of concrete. The proportion of each concrete type follows the proportion of concrete by Wiswamitra et al. [11]. Figure 8 shows some of the test objects and the implementation of making test objects in the laboratory.

**Table 5.** The mixtures composition of each type of concrete and the slump value.

| Concrete mix name | Mixtures composition | | | | Slump value (mm) |
|---|---|---|---|---|---|
| | Cement (kg) | Water (liter) | Coarse aggregate (kg) | Fine aggregate (kg) | |
| FC-N | 460 | 233 | 713.76 | 773.24 | 55 |
| FN-CPRha | 460 | 233 | 353.50 | 773.24 | 50 |
| FN-CPCm | 460 | 233 | 407.64 | 773.24 | 45 |
| FC-PRha | 460 | 233 | 353.50 | 466.71 | 60 |
| FC-PCm | 460 | 233 | 407.64 | 523.91 | 50 |


a b c d e

**Figure 8.** Making specimens in laboratory. (a) Slump test, (b) cylinder specimens, (c) curing, (d) cylinder with sulfur cap, and (e) flexure tensile test specimens.

### *3.3. Stage III—testing the mechanical characteristics of lightweight concrete*

Complete concrete test results in concrete density and concrete mechanical characteristics after heating at various temperatures can be seen in Tables 6 and 7.

**Table 6.** The density and the compressive strength after heating at various temperatures.

| Concrete mix name | Density (kg/m$^3$) | Compressive strength (MPa) | | | | |
|---|---|---|---|---|---|---|
| | | 30 °C | 100 °C | 200 °C | 300 °C | 400 °C |
| FC-N | 2123.53 | 39.30 | 37.16 | 35.01 | 31.55 | 30.04 |
| FN-CPRha | 1785.01 | 33.26 | 24.96 | 17.11 | 14.42 | 4.15 |
| FN-CPCm | 1840.49 | 37.92 | 27.48 | 21.07 | 15.07 | 4.89 |
| FC-PRha | 1578.72 | 23.62 | 17.94 | 16.14 | 10.79 | 1.55 |
| FC-PCm | 1672.82 | 23.94 | 20.16 | 15.89 | 9.88 | 2.54 |

**Table 7.** The splitting tensile strength after heating at various temperatures and the flexural tensile strength.

| Concrete mix name | Splitting tensile strength (MPa) | | | | | Flexural tensile strength (MPa) |
|---|---|---|---|---|---|---|
| | 30 °C | 100 °C | 200 °C | 300 °C | 400 °C | |
| FC-N | 2.74 | 2.51 | 2.35 | 2.00 | 1.82 | 4.50 |
| FN-CPRha | 1.65 | 1.51 | 0.88 | 0.62 | 0.18 | 2.87 |
| FN-CPCm | 1.89 | 1.45 | 0.96 | 0.59 | 0.23 | 3.45 |
| FC-PRha | 1.00 | 0.99 | 0.88 | 0.48 | 0.06 | 1.19 |
| FC-PCm | 1.02 | 0.73 | 0.57 | 0.50 | 0.10 | 1.33 |

3.3.1. The density, the compressive strength, and the cracks after heating

The results of the compressive test on the reference specimen (i.e., the sample with room temperature = 30 °C) for all types of concrete and the results of the concrete density test show that all kinds of concrete with synthetic aggregates produce concrete that falls within the criteria for structural lightweight concrete. ACI 213R-87 [36] requires that structural lightweight concrete is concrete that uses lightweight aggregates with air-dry weight at 28 d ranging from 1440–1850 kg/m$^3$ and with a compressive strength of more than 17.24 MPa. If the density and compressive strength of concrete are sorted from the largest to the smallest value, it will be seen in Figure 9. It appears that concrete with fine natural aggregates (FN-CPRha and FN-CPCm) ranks first in terms of density and compressive strength, compared to concrete with all aggregate fractions in the form of synthetic aggregates (FC-PRha and FC-PCm). In the figure, it can be seen that the pattern of reduction in the compressive strength of concrete is sharper than the decrease in concrete density.

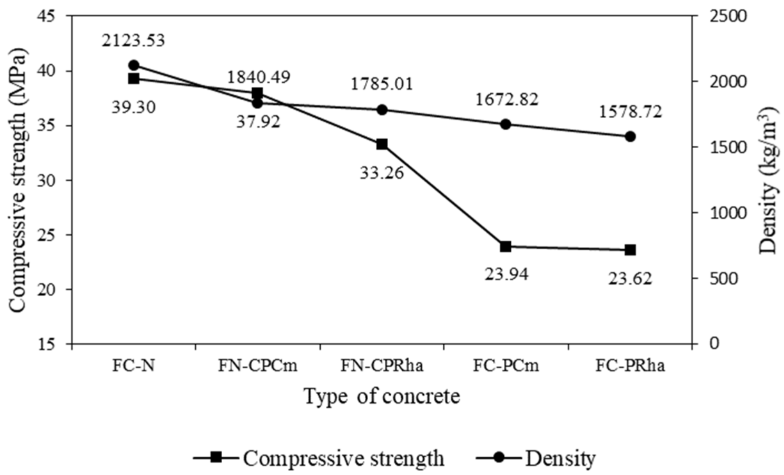


**Figure 9.** Compressive strength and density of each type of concrete.

Meanwhile, concrete with PA II produces a density and compressive strength of concrete that is higher than that of PA I. Reference concrete, namely concrete with natural aggregates, ranks first both in density and compressive strength of concrete. Figure 10 shows the value of concrete structural efficiency at the age of 28 d which is the quotient value of the compressive strength of the concrete with the value of the density of the concrete. The figure shows that concrete with fine natural aggregate and coarse aggregate from filler-PET (PA I or PA II) has a higher structural efficiency value than concrete using natural local aggregates.

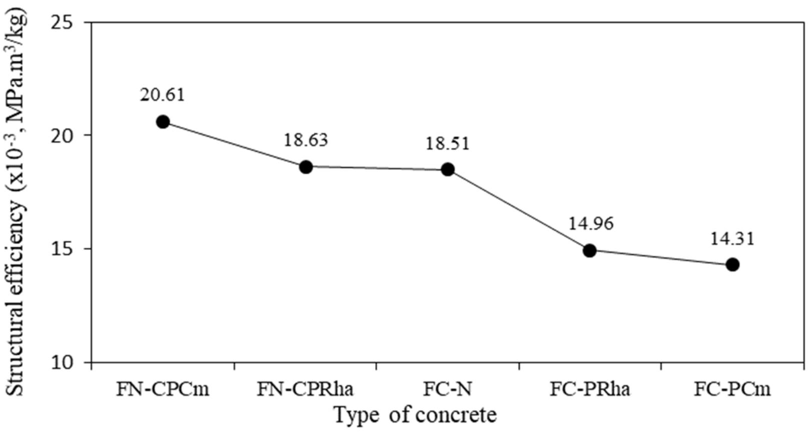


**Figure 10.** Structural efficiency values for each concrete type.

The test results on concrete after heating at various temperatures show that the compressive strength of the concrete decreases at higher heating temperatures. The decrease in the compressive strength of concrete with plastic aggregates is sharper than that of reference concrete (FC-N), Figure 11. In more detail, it can be seen that the decrease in compressive strength can be seen from the heating temperature T = 100 °C, both for reference concrete and concrete with artificial aggregates. A significant reduction in compressive strength occurs in concrete with plastic aggregates; this is due to the fine cracks caused by heating, which can be seen using a digital microscope, as shown in Figure 12. The crack width is measured from 0.004 to 0.011 mm. Cracks like these are not visible in reference concrete. Cracks in concrete due to heating can occur due to differences in the thermal expansion of the aggregate and the cement matrix. The presence of heat causes the concrete to expand outward which creates internal tensile stresses which in turn cause internal cracks that extend to the surface [37]. Overheating will also cause chemical changes that cause microcracking so that the integrity and strength of the concrete decrease.

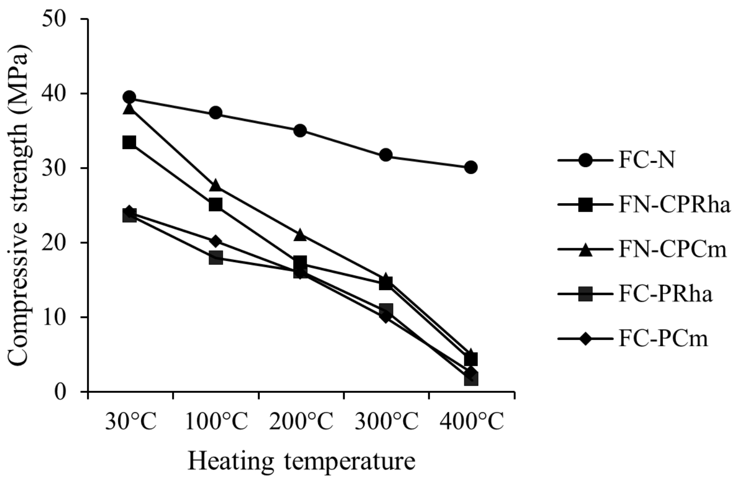


**Figure 11.** Relationship between heating temperature and compressive strength.

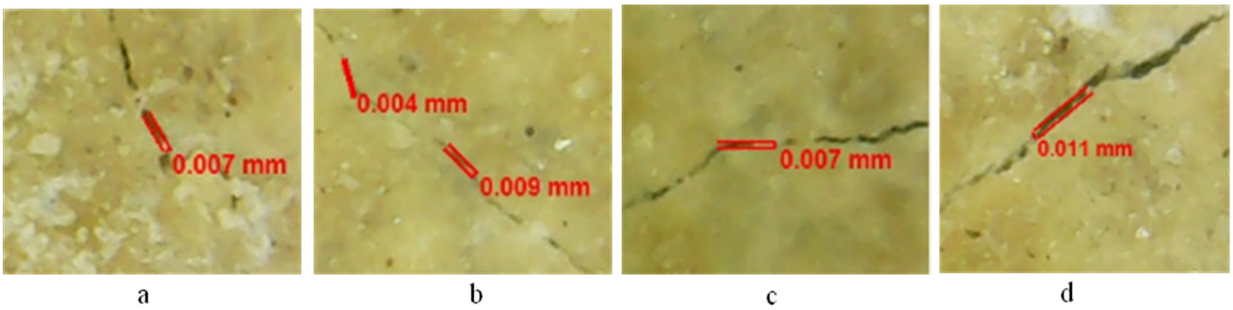


**Figure 12.** Cracks in concrete cylinder with plastic aggregate after heating at 100 °C. (a) FN-CPRha, (b) FN-CPCm, (c) FC-PRha, and (d) FC-PCm.

The reference concrete started to have fine cracks (seen with a digital microscope) when the heating temperature up to 200 °C, while in concrete with synthetic aggregates, the crack width became wider (visible to the naked eye) as shown in Figure 13 and the compressive strength of the concrete is decreasing. It can be seen that the cracks in concrete with PA II (FN-CPCm and FC-PCm) are wider than concrete with PA I (FN-CPRha and FC-PRha). At a heating temperature of 300 °C, cracks in the concrete with plastic aggregates were visible more and more clearly. The cracks in the cylindrical concrete were further clarified using a marker and photographed as shown in Figure 14. At heating temperature T = 400 °C, the concrete specimen with plastic aggregate began to burn and blackened, indicating that the plastic aggregate from PET concrete had decomposed. It can also be seen in the post-heating concrete cylinder that the cracks in the concrete with PA II are more numerous and wider than the concrete with the PA I aggregate. Figure 15 shows the fracture surface of the concrete cylinder in the specimen after heating at 400 °C which shows that the decomposition and evaporation process of PET plastic aggregates due to heat that has exceeded its melting point occurs in the area around the perimeter of the concrete cylinder to a depth of ±2 cm. Figure 16 is the SEM photo results on the FN-CPRha specimens after heating at each temperature. The photo is focused only on the plastic aggregate section, in this case, the Type I/PA I plastic aggregate (rice husk ash-PET aggregate). In the series of photos, it can be seen that the PA I aggregate after heating at a temperature of 100 °C (Figure 16a), 200 °C (Figure 16b), 300 °C (Figure 16c), and 400 °C (Figure 16d), which shows that the higher the heating temperature, the plastic aggregate shows various levels of deterioration, namely cracks, the rougher the surface is at the increasingly high, even decomposition occurs, especially in the aggregate after heating at 400 °C which is indicated by the rough and wavy surface of the aggregate.

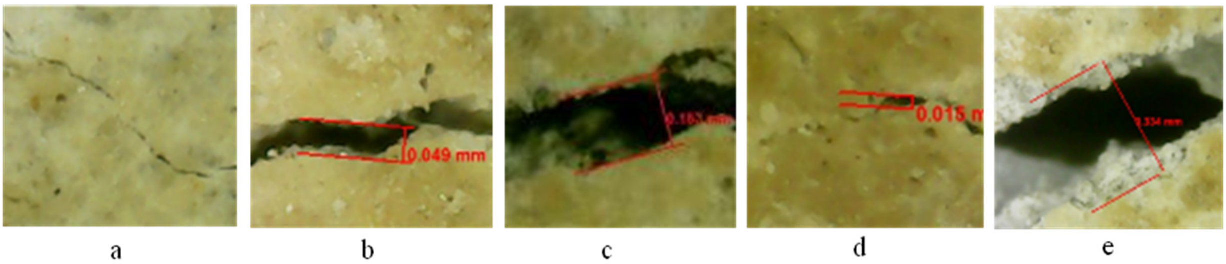


**Figure 13.** Cracks in concrete after heating at 200 °C. (a) FC-N, (b) FN-CPRha, (c) FN-CPCm, (d)FC-PRha, and (e) FC-PCm.

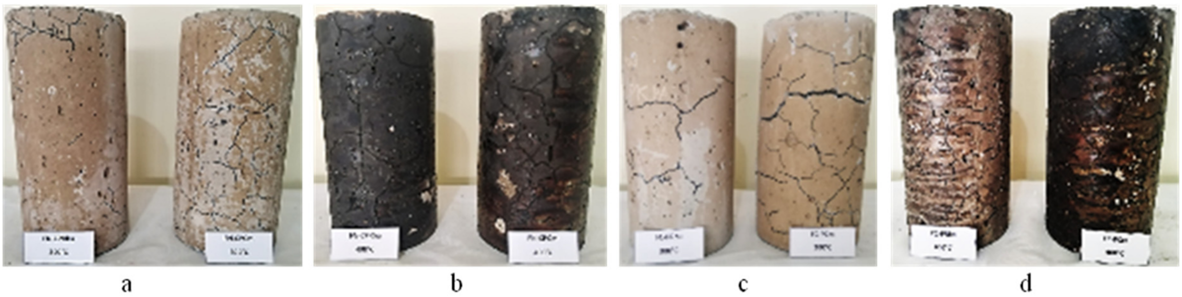


**Figure 14.** Cracks in concrete cylinder. (a) FN-CPRha and FN-CPCm after T = 300 °C, (b) FN-CPRha and FN-CPCm after T = 400 °C, (c) FC-PRha and FC-PCm after T = 300 °C, (d) FC-PRha and FC-PCm after T = 400 °C.

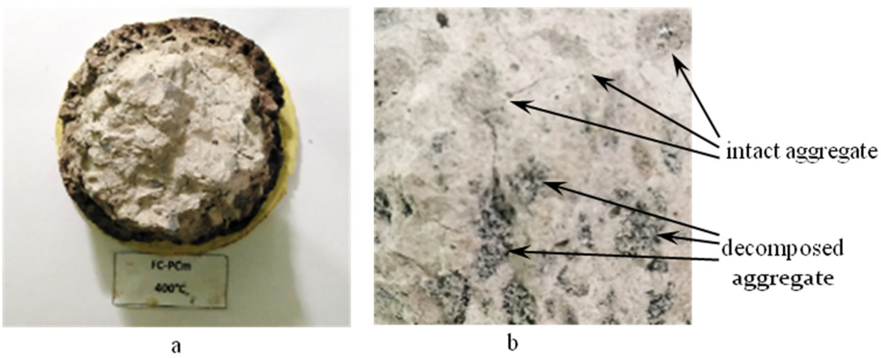


**Figure 15.** Photo of specimen after heating to 400 °C. (a) Perimeter of concrete cylinder that has undergone a decomposition process due to heating (FC-PCm). (b) Some of the plastic aggregate in the concrete (in the lower half of the photograph) which is the outer portion of the cylindrical concrete specimen appears to have decomposed and evaporated (FC-PRha).

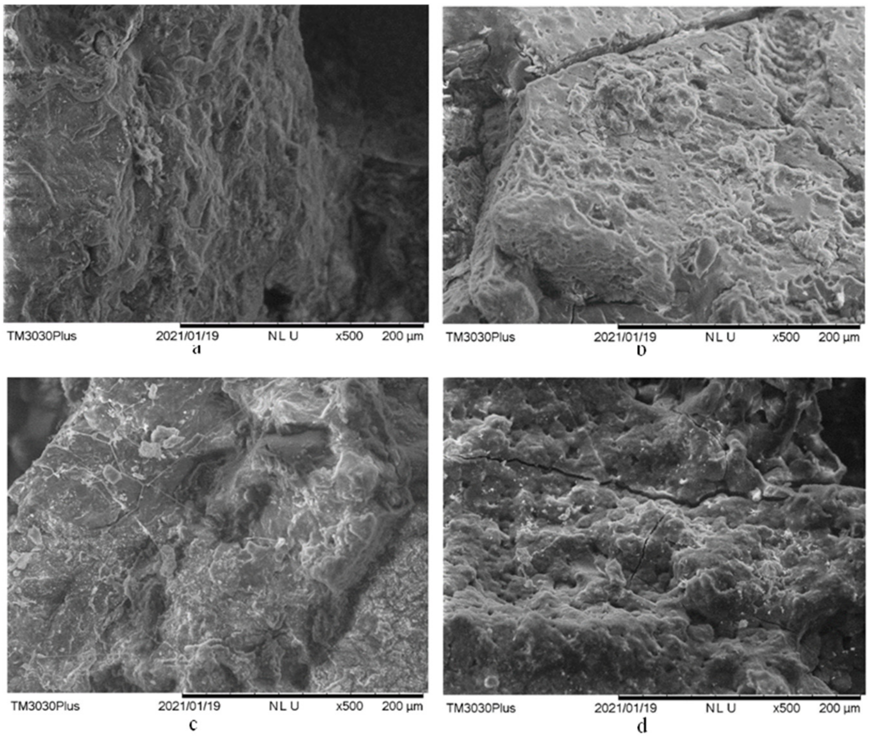


**Figure 16.** SEM photo results on FN-CPRha specimens, especially in the plastic aggregate type I/PA I (rice husk ash-PET aggregate) section at each heating temperature. (a) 100 °C, (b) 200 °C, (c) 300°C, and (d) 400 °C.

3.3.2. The splitting tensile strength

Data from the split tensile strength test for all types of concrete can be seen in Table 7 and illustrated in Figure 17. As in the compressive strength results, the split tensile strength shows a decreasing pattern with the same sequence of concrete types arranged from the largest to the smallest value. The more plastic content in the concrete (Figure 17a) and the higher the heating temperature (Figure 17b) the lower the tensile capacity of the concrete.

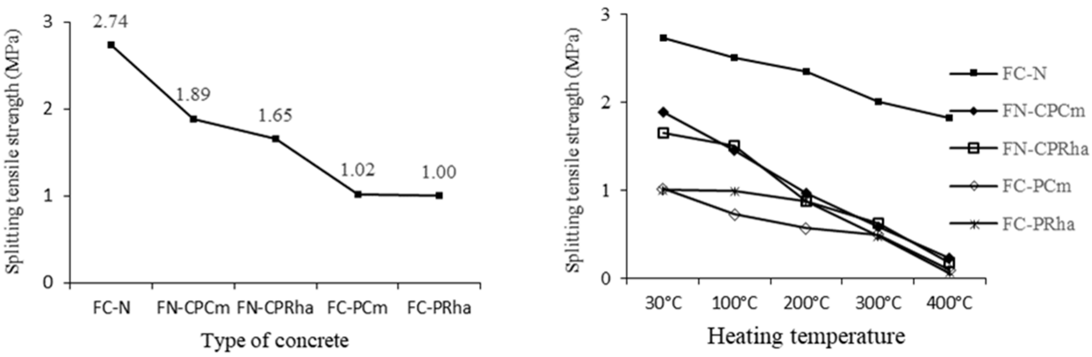


**Figure 17.** Tensile strength curve (a) each of concrete, (b) relationship between heating temperature and split tensile strength for each type of concrete.

### 3.3.3. The flexural strength

The flexural strength test was carried out using the third point loading method (Figure 5c). Figure 18 illustrates the flexural tensile strength value for each concrete, which shows a decreasing pattern, such as compressive strength and split tensile strength.

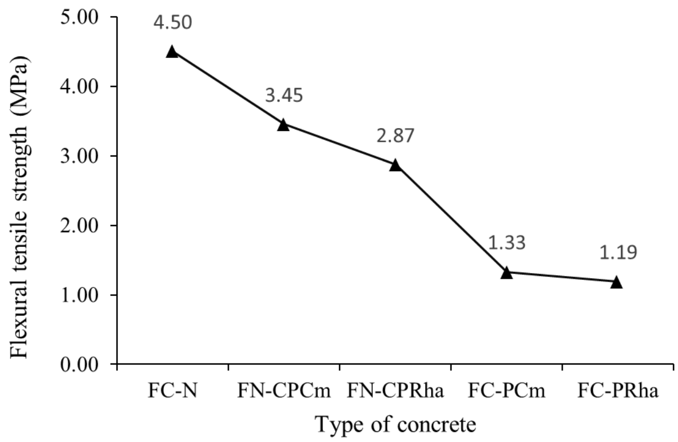


**Figure 18.** Flexural tensile strength for each type of concrete.

Figure 19 shows the fracture surface of the beam specimen after flexural tensile test. The type of FC-N reference concrete has the roughest fracture surface, followed by concrete using natural sand (FN-CPRha and FN-CPCm), and the smoothest is concrete with all synthetic aggregates (FC-PRha and FC-PCm).

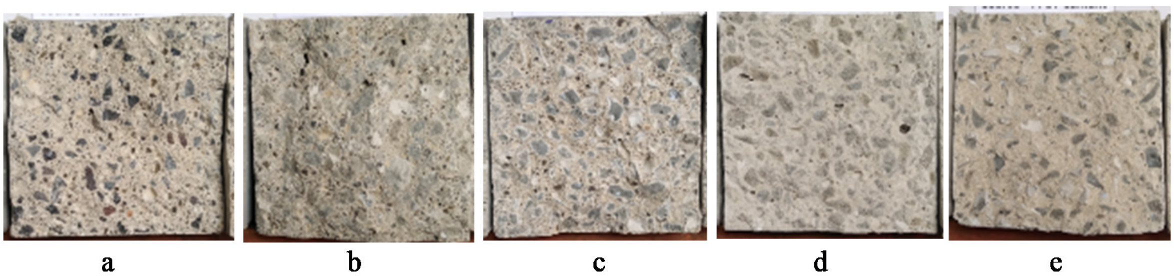


**Figure 19.** The fracture surface of the flexural tensile test specimen for each type of concrete (a) FC-N, (b) FN-CPRha, (c) FN-CPCm, and (d) FC-PRha (e) FC-PCm.

## 4. Conclusions

After carrying out research on the heat resistance of lightweight concrete with plastic aggregate from PET (Polyethylene Terephthalate)-mineral filler, several conclusions can be drawn:

- Plastic aggregate type I (PA I) produce a roughen and more porous surface of the aggregate, has greater water absorption, has a smaller density and specific gravity than type II plastic aggregate (PA II).

- The use of PA I causes the density and mechanical characteristics of concrete to be smaller than that of concrete using PA II.
- The use of PA I and PA II both as a substitute for coarse aggregate fraction only or as a substitute for all-natural aggregate fractions is capable of producing structural lightweight concrete.
- The use of PA I and PA II as coarse aggregates (while fine aggregate uses natural sand) can produce greater structural efficiency of concrete compared to concrete with whole natural aggregates (reference concrete).
- Cracks in concrete due to heating will be less in number and with a smaller crack width when using PA I than PA II.
- Decrease in the mechanical characteristics of concrete with plastic aggregate and reference concrete due to heating, starting from the first temperature of treatment, which is 100 °C.
- The decrease in the compressive strength and tensile strength of concrete with plastic aggregates due to heating looks more drastic than that of reference concrete.
- The mechanical characteristics and density of concrete with plastic aggregates will be smaller than that of reference concrete.

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## Conflict of interest

All authors declare no conflicts of interest in this paper.

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