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# COMPRESSIVE STRENGTH OF RECYCLED AGGREGATED CONCRETE FROM CONCRETE WASTE AND PLASTIC WASTE

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**ABSTRACT:** Currently, the main material used in various construction materials is concrete, which is a composite material containing cement, water, and aggregate. These ingredients are materials derived from sometimes limited natural resources. In addition, economic growth today uses a variety of materials and generates a lot of waste that directly affects the environment. This research compared concrete mixes using the wastes of concrete piles as aggregate and replacing 10, 20, or 30 % (v/v) of fine aggregates with plastic waste (PW) from the recycling process, called Recycled Aggregate Concrete or RAC. Sensors were installed on the concrete surface of samples to determine the early movement of concrete particles under compressive load. It was found that the RAC developed greater compressive strength compared to ordinary concrete using natural ingredients. Increasing the proportion of fine aggregate replacement with plastic waste in RAC decreased the maximum compressive strength and the rate of compressive strength development. In a similar manner, the repeated use of RAC as aggregate affected the compressive strength of the concrete and the rate of development. Increasing plastic replacement in the recycled concrete had a more substantial impact on recycled concrete strength than increasing the number of recycle times. PW replacement of 10 % of the fine aggregates is recommended.

*Keywords: Acoustic Emission, Fine Aggregate, Plastic Waste, Recycled Aggregate Concrete, Waste Concrete*

## 1. INTRODUCTION

Nowadays, concrete is commonly used as an engineering material in almost all construction categories, including residences, high-rise buildings, and other types of infrastructure. The main components of concrete are cement, water, and aggregates, accounting for approximately 70–80 % of the total concrete volume. Approximately 12.6 billion t of concrete are used worldwide, consuming 1.6 billion t of cement, 10 billion t of aggregates, and 1 billion t of mixing water [1]. Considering only projects in Thailand under the supervision of the Department of Highways and the Department of Rural Roads, constructed concrete roads have a total length of 4,555 km [2]. Aggregates, the main constituents of concrete, are vital to concrete strength and concrete durability. The selection of good coarse aggregates and fine aggregates will increase the strength of concrete [3]. However, the increasing development of the construction industry and the associated demand for concrete consumption is placing a major load on limited natural resources, such as limestone, granite, and basalt, which are utilized as coarse aggregate materials [4]. Although stone quarrying has a lower environmental impact than mining and oil drilling, it still causes health and well-being issues for neighboring residents, due to the dust that deteriorates the air quality, destroys habitats for a variety of organisms, and severely affects the environment [5].

Natural stone quarrying has a major environmental impact in terms of $CO_2$ emissions. Processing 1,000 kg of natural aggregate material emits 20 kg of $CO_2$. Blasting and crushing operations in a stone quarry produce particulate matter less than 10 µm in diameter ($PM_{10}$) and fine particles less than 2.5 µm in diameter ($PM_{2.5}$), as well as dust from loading and transporting the stone products to various concrete production sites. Alternative aggregate materials, which are mostly waste material or industrial waste, are currently used to replace aggregate materials [6] to address the increasing pressure to decrease natural aggregate consumption. Furthermore, if no alternative aggregate utilization is available, industrial waste will substantially increase, especially in companies with poor waste disposal in terms of environmental friendliness [7].

The use of recycled aggregates in concrete mixes is a low-cost and environmental-friendly alternative that can assist to substantially reduce the energy costs in concrete production and associated waste and pollution [8]–[10]. The importance of waste recycling for utilization in the construction field is a byproduct of the large amounts of products or industrial wastes considered to be no longer in use [11]. In current concrete manufacture, the introduction of industrial products reduces the negative impact on the environment associated with waste [12]. As a result, the feasibility of utilizing recycled aggregate in concrete mixes, especially as aggregate material, has been thoroughly studied, including the investigation of the mechanical properties of recycled coarse aggregate and fine aggregate [13]–[15]. Utilization of these recycled aggregates can reduce production costs and the dependence on limited natural resources [16].

In the 20th and early 21st centuries, research has shown that wastes, whether in a solid, liquid, or toxic form, have a major impact on the modern era and on economic development [17]–18]. Waste management remains a major challenge, especially in urban areas of low and middle-income countries. Plastic waste (PW) is of national and global concern [19]. It is one of the many factors that negatively affect the environment, and it impacts on other aspects, such as the difficulty of waste recycling and its limited reuse. Plastic is an important type of waste with a high environmental impact [20] that is gaining increased global attention. PW has impacts on both land and sea ecosystems through factors that include water pollution and soil contamination that threaten the survival of wildlife and oceans [21]–22]. Only 50 % of PW is recycled, while 90 % of the rest is sent to landfills [23]–[24]. Plastics have been identified as one of the most promising materials to reduce the carbon emissions coupled with steel, aluminum, and cement. Mechanical recycling of PW is estimated to emit approximately 1.4 t $CO_2$/t-plastic, which is less than the 5.1 t of $CO_2$ emissions in new plastic production that accounts for 30% [25].

The importance of reusing and recycling waste is to reduce environmental pollution and conserve non-renewable natural resources [26]. Other studies reported that plastics could be recycled for use as a material, which has become an increasingly prominent research topic in recent years [27], especially manufacturing Recycled Plastic Concrete for use as a partial replacement for natural aggregate to minimize $CO_2$ emissions in the concrete industry [20], [28]–[29].

## 2. RESEARCH SIGNIFICANCE

The current research involved a comparative study of concrete mixes using the wastes of concrete piles as aggregates to make Recycled Aggregate Concrete (RAC) by replacing 10, 20, or 30 % (v/v) of fine aggregates with the Plastic Waste (PW) from the recycling process. The compressive strength of RAC at 7, 14 and 28 days of water curing was investigated. Acoustic sensors were installed on the concrete surface to measure the movement of concrete particles during compression testing. Acoustic Emission (AE) was investigated during loading for all samples. Outputs were studied and summarized.

## 3. MATERIALS AND METHODS

### 3.1. Materials of Concrete Mixes

*3.1.1 Recycled aggregate concrete*

The main aggregate material used in the concrete mixture was concrete waste. At present, when constructions are demolished, these materials will be used for land reclamation and in road embankments. The waste concrete used in the current study was crushed concrete obtained from piles (Fig. 1).

Fig. 1 Recycled Aggregates from Pile Waste

The mix size distribution of the recycled aggregates obtained from the waste piles is shown in Fig. 2.

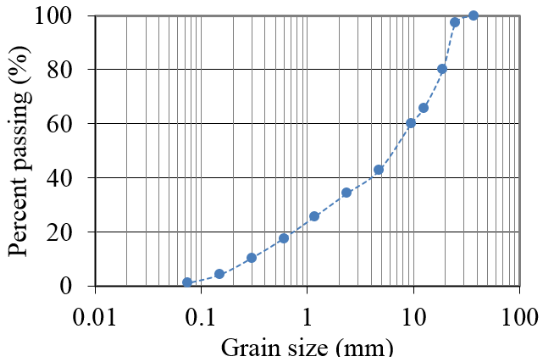



Fig. 2 Gradation Curve of Recycled Aggregates

*3.1.1 Plastic waste from recycling process*

Another ingredient was PW obtained after a recycling separation process using specific gravity. If the specific gravity of the plastic is greater than the specific gravity of water, then it will not be recycled. Fig. 3 shows some PW.

Fig. 3 Plastic Waste Used as a Replacement for Fine Aggregate in Concrete Mixes

### 3.2. Concrete Sample Preparation

The ingredients of the concrete utilized in this research consisted of concrete waste obtained from pile heads, PW used as a replacement for fine aggregates, Type I cement, and water. The concrete obtained from the pile heads was crushed and distributed as aggregate and mixed with cement and water (Fig. 2). The aggregate materials used in the concrete mix design contained 10, 20, or 30 % substitution with an equal volume of fine (passed through a 4.75 mm sieve), recycled aggregate. The PW ingredient was used to replace fine aggregate. Fig. 4 illustrates the compositions of the 10 samples of concrete mix used in this study. The concrete mix parameters after each round of recycling are indicated in Table 1.

For the investigation, A denoted the concrete obtained from the pile head concrete crushed to be aggregate and mixed with cement and water, while A10, A20, and A30 represent concrete obtained from recycled aggregates mixed with cement and water and containing 10, 20, and 30 % PW by volume of fine aggregate, respectively. B was the concrete sample composed of crushed sample A, which was utilized as recycled aggregate, mixed with cement, water, and 10 % by volume of fine aggregate PW. Concrete samples B10 and B20 were made from recycled aggregate (A10 and A20, respectively) mixed with cement and water that contained 10 % by volume of fine aggregate by PW. C was the concrete sample composed of crushed sample B to be used as recycled aggregate mixed with cement, water, and PW using 1 0% by volume of fine aggregate PW. C10 was concrete obtained from recycled aggregate (B10) mixed with cement and water containing 10 % by volume of fine aggregate PW. D was the concrete sample composed of crushed sample C to be used as recycled aggregate mixed with cement and water that contains 10 % by volume of fine aggregate PW, as shown in Fig. 4.

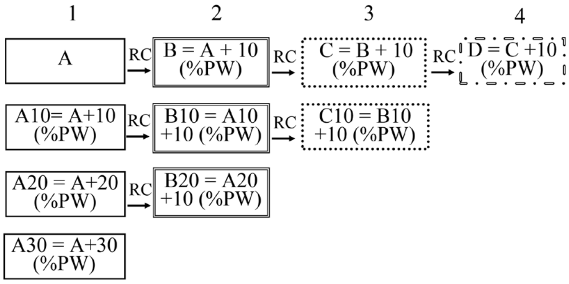



Fig. 4 Flow Chart of Recycled Concrete Sample Preparation

Table 1 Concrete Mix Proportions

| RC Round | Type | RCA | PW | Water | Cement | W/C | Slump Test |
|---|---|---|---|---|---|---|---|
| | | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | $kg/m^3$ | - | cm |
| 1 | A | 541.85 | - | 63.74 | 126.20 | 0.51 | 8.0 |
| 1 | A10 | 518.13 | 10.79 | 65.53 | 126.20 | 0.52 | 8.0 |
| 1 | A20 | 494.42 | 21.57 | 65.36 | 126.20 | 0.52 | 8.5 |
| 1 | A30 | 470.69 | 32.36 | 67.11 | 126.20 | 0.53 | 8.7 |
| 2 | B | 518.13 | 10.79 | 65.53 | 126.20 | 0.52 | 8.0 |
| 2 | B10 | 532.71 | 10.79 | 65.49 | 126.15 | 0.52 | 8.2 |
| 2 | B20 | 532.71 | 10.79 | 65.91 | 126.15 | 0.52 | 8.2 |
| 3 | C | 532.71 | 10.79 | 65.49 | 126.15 | 0.52 | 8.2 |
| 3 | C10 | 493.80 | 10.00 | 63.06 | 118.74 | 0.53 | 8.0 |
| 4 | D | 493.80 | 10.00 | 63.06 | 118.74 | 0.53 | 8.0 |

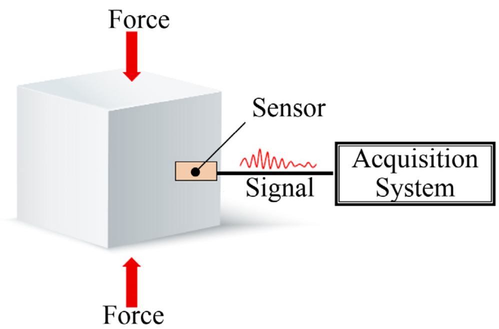
### 3.3. Sensor Installation for Detecting Crack Propagation in Concrete Particles

The concrete was mixed and prepared in cubes (15 cm each dimension) for 7, 14, and 28 days of water curing prior to testing. Before the compression test, a sensor was installed to measure the movement of the tested concrete particles, as shown in Fig. 5(a). AE methods are commonly used in concrete structures. The results obtained were standardized for inspection and evaluation of the basic infrastructure based on analysis of the AE behavior of concrete under compression that can then be used to assess and classify the damage levels of structures based on non-destructive assessment using the AE data [30]. A signal filtering method (AE counts) used the number of peak flows greater than a given threshold flow. Duration was the interval between the first and last times the detection threshold was exceeded, while the rise time (RT) was the compressive loading period between the onset and the occurrence of the maximum amplitude. The risetime per peak magnitude (RA) value and the average frequency (AF) are two characteristic waveform indicators defined by equations (1) and (2) [31].

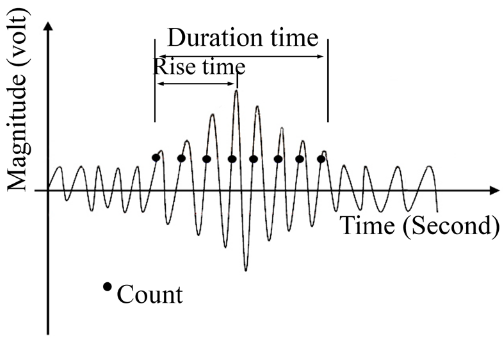
$$\mathrm{RA} = \frac{\text{Rise time}}{\text{Peak Magnitude}} \tag{1}$$

$$AF = \frac{\text{Counts}}{\text{Duration}} \quad (2)$$

AE hits and count numbers are commonly used to monitor damage. When the RA and AF reports were correlated with crack mode characteristics, it was discovered that the tension mode of cracking, such as in concrete, resulted in greater AF values and lower RA values. Measurement using the AE sensor attached to the surface of the material means that unlike other non-destructive testing techniques, AE monitoring is a passive monitoring technique that detects AE signals only when cracks occur. The characteristic parameters of commonly used AE signals are indicated in Fig. 5(b). The AE signal strength is the AE relative energy [32]. An example of sensor installation to measure the particle movement behavior of the concrete sample is shown in Fig. 6. A compressive strength test was used to continuously apply pressure at a constant rate of 0.5 MPa/s until the concrete failed to withstand the compressive load.




(a) Sensor Installation




(b) Characteristics of AE Signal

Fig. 5 Sensor Installation and Characteristics of AE Signal

## 4. RESULTS AND DISCUSSION

### 4.1. Physical Properties of Recycled Composites

The aggregates used in the mixture were coarse aggregate (2.36 bulk specific gravity) and fine aggregate (2.35 bulk specific gravity) that were obtained from pile waste that had been processed using a jaw crusher unit based on the required gradation. Table 2 shows the results of the physical property tests on the aggregates. The specific gravity of Type 1 Portland Cement was 3.14. The specific gravity of the PW used in this research was 1.07.

Fig. 6 Installed Sensor to Measure Magnitude ($Volt^2$) in Concrete Samples

Table 2 Physical Properties of Recycled Aggregate

| Property | Fine Aggregate | Coarse Aggregate | Test Method |
|---|---|---|---|
| Los Angeles Abrasion, (%) | | 18.88 | ASTM C 131 |
| Flakiness Index, (%) | | 22.00 | BS 812 |
| Elongation Index, (%) | | 25.11 | BS 812 |
| Unit Weight, ($Kg/m^3$) | 1441.7 | | ASTM C |
| Soundness Test of Aggregate, (Solution of Sodium sulfate), (%) | 10.72 | 15.32 | ASTM C 88 |

The development of compressive strength for the RAC samples is illustrated in Fig. 7. The 4 samples of A, A10, A20, and A30, after 7–14 days of water curing, had increases in compressive strength of 14.86, 12.53, 10.26, and 11.54 %, respectively, while after 14–28 days of water curing, the increases were 7.25, 9.50, 1.06, and 3.67 %, respectively. For B, B10, and B20 after 7–14 days of water curing, the increases were 17.22, 9.48, and 8.07 %, respectively, while after 14–28 days of water curing, the increases were 11.12, 3.87, and 1.57 %, respectively. After 7–14 days of water curing, samples C and C10 had increases of 6.16 and 10.28 %, respectively, and after 14–28 days of water curing, the increases were 1.23 and 4.30 %, respectively. The development of compressive strength for sample D was 2.27% after 7–14 days of water curing and 3.05 % after 14–28 days of water curing. The development of compressive strength in each round showed a limitation as an increase in PW.

For the sample with 10 % PW of the volume of fine aggregate, after RC rounds 1 and 2, the compressive strengths for samples A10 and B after 7–14 days of water curing were 12.53 and 17.22 %, respectively, while after 14–28 days of water curing, the increases in compressive strength development were 9.50 and 11.12 %, respectively. For 20 % PW of the volume of fine aggregate, in the samples for rounds 1, 2, and 3, the sample groups A20, B10, and C, after 7–14 days of water curing, had increased strengths of 10.26, 9.48, and 6.16 %, respectively, while the increases were 1.06, 3.87, and 1.23 %, respectively, after 14–28 days of water curing. The development of compressive strength with 30 % PW of the volume of fine aggregate in rounds 1, 2, 3, and 4, the sample groups A30, B20, C10, and D. For 7–14 days of water curing, the increased compressive strengths were 11.54, 8.07, 10.28, and 2.27 %, respectively, while after 14–28 days of water curing, the increases were 3.67, 1.57, 4.30, and 3.05 %, respectively. These above results showed that for the same percentage of PW, as the number of rounds increased, the compressive strength was lower for the same curing time.

Increasing the quantity of the PW in RAC, as shown in Fig. 7, in each round of sample preparation reduced the maximum compressive strength of the samples. For round 1, the maximum compressive strengths of RAC mixed with PW at 10, 20, and 30 % by volume replacement of fine aggregates (A, A10, A20 and A30) after 7 days of water curing were decreases of 21.55, 30.97, and 41.24 %, respectively, compared to 0 % PW replacement of fine aggregates.

After 14 days of water curing, the decreases in compressive strength were 23.14, 33.74, and 42.93 %, respectively, and after 28 days of water curing, the values were 21.53, 37.56, and 44.84 %, respectively. During round 2, composed of B, B10 and B20, the maximum compressive strength decreases of recycled concrete mixed with PW at 10, 20, and 30 % by volume replacement after 7 days of water curing were 1,03 and 8.06 %, compared to B and, after 14 days, were 7.57 and 15.23. The compressive strength decreases after 28 days were 13.60 and 23.52. For round 3, the strengths of C and C10 were compared. The decreases were 23.70, 20.75, and 18.34 % for 7, 14, and 28 days of water curing, respectively. The compressive strength using 10 % of PW replacement for each round resulted in less.

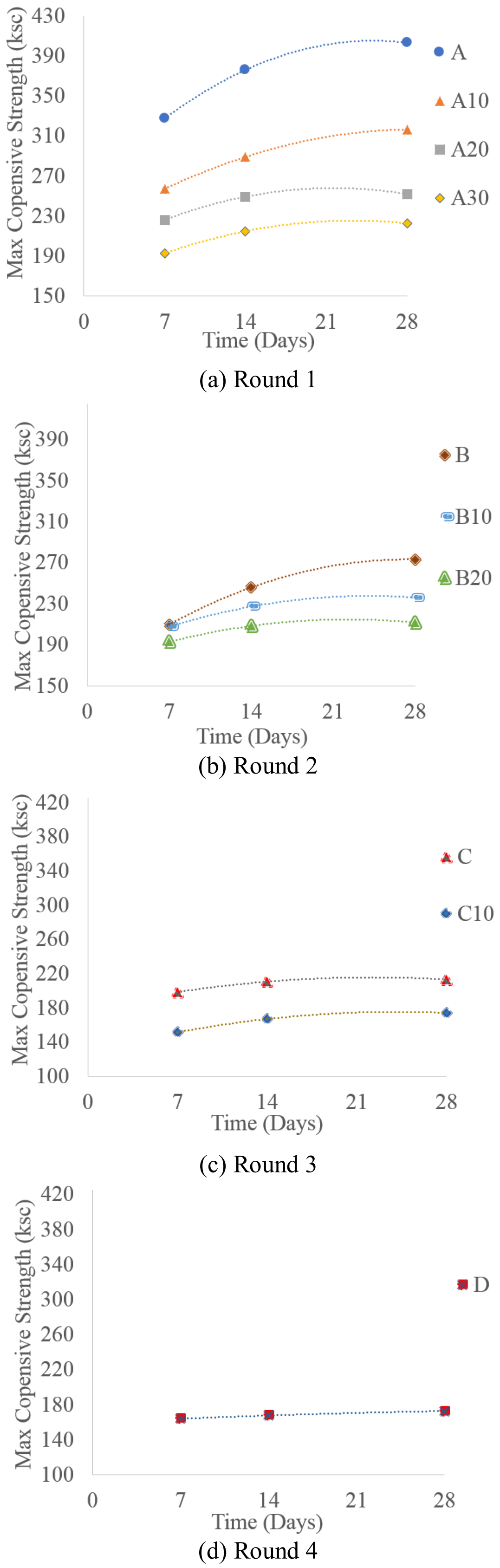



Fig. 7 Maximum Compressive Strength of Recycled Concrete after 7, 14, and 28 Days of Water Curing

difference in compressive strength compared to the lowest replacement in that round. As the number of rounds increased, the development of compressive strength to the curing time of normal usual concrete reduced. The increase in the amount of added PW had an impact on the maximum strength of the recycled concrete. The percentage of PW replacement in round 1 had less impact on the maximum strength of the recycled concrete than in subsequent rounds.

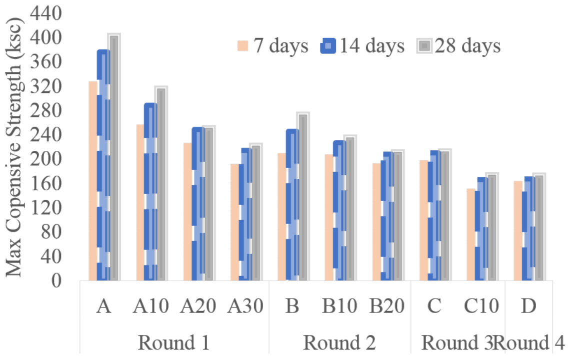
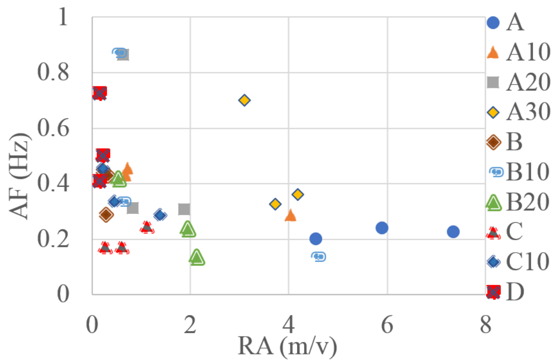


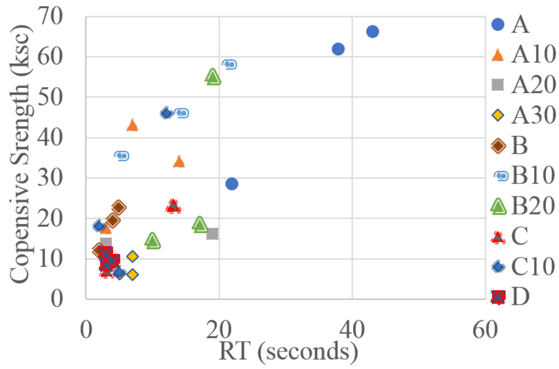

Fig. 8 Comparison of Maximum Compressive Strength of Recycled Concrete after 7, 14, and 28 Days of Water Curing in Each Recycling Cycle

During the AE compression testing, the RA and AF were calculated for all RAC samples. The calculation results of tested samples that were cured after 7, 14, and 28 days are plotted in Fig. 9(a), 10(a), and 11(a), respectively. The RA values for 0 % PW tended to be higher than the others for all periods of curing. The higher the % PW replacement, the lower the RA value, with all tested samples having RA values of less than 3. The AF values for all test samples were in the range 0.10–0.50, while the AF value for 0 % PW was more consistent than the others, with the other samples replacing fine aggregate with PW having no relationship between RA and AF.

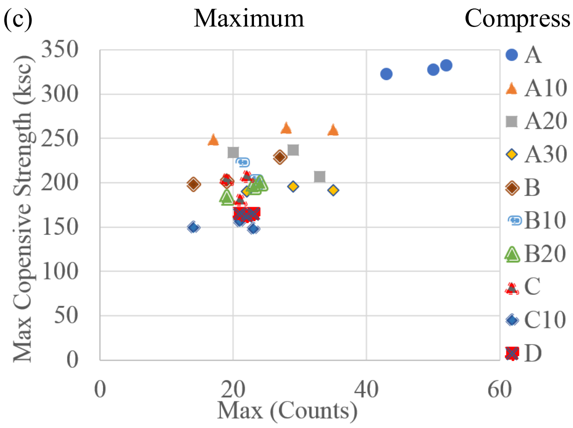
The relationships between the RT and the count number to the compressive strength of the recycled concrete samples are shown in Fig. 9(b), 10(b), 11(b) and Fig. 9(c), 10(c), 11(c). The count number was higher when the percentage of PW replacement was lower, in the same manner as the compressive strength. RT also showed similar behavior, but the boundaries of the RT value were more scattered than for the count number. The count number was in the range 10–50 for all samples, indicating that the less the PW replacement for fine aggregate, the greater the count number. RT did not have any consistent range with curing time; However, the amount of PW replacement was related to the RT, with RT tending to decrease with an increasing amount of PW. The increasing amount of PW in the recycled concrete and the greater the number of repeat uses of the aggregate from recycled concrete showed the impact on AE, which could be explained by the value and rate of compressive strength of the recycled concrete samples. This may have been why the lower the level of PW replacement, the fewer micro cracks there were in the aggregate after increased cycles of crushing. Since the PW surface is slippery and platelike while the fine aggregate shape is more like an angular sphere, the appearance of discontinuity planes on




(a) Changes in RA and AF Values at Commencement of Concrete Particle Movement

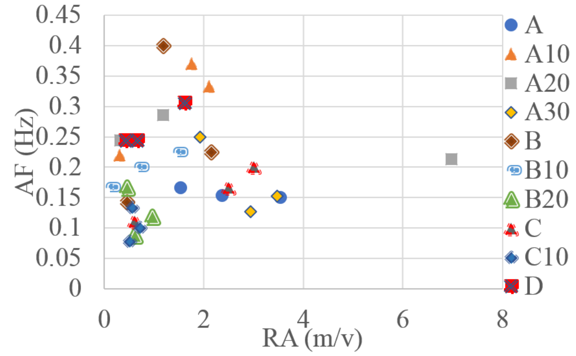



(b) Compressive Strength at Commencement of Concrete Particle Movement

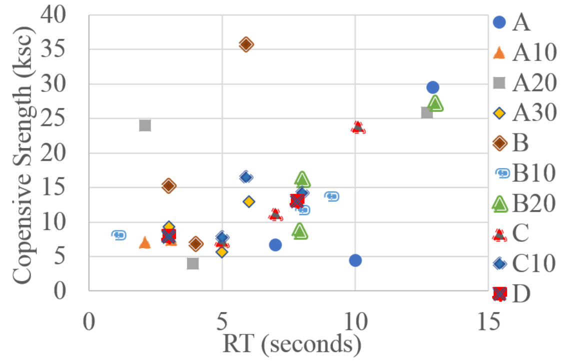



(c) Compressive Strength and Maximum Number of Revolutions in Concrete Movement

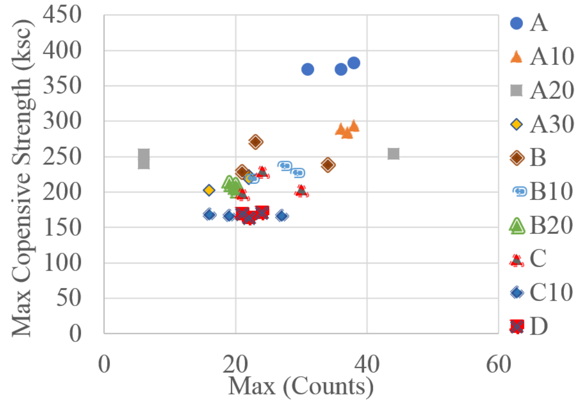
Fig. 9 Results of Measuring Compressive Behavior of Concrete after 7 Days of Water Curing




(a) Changes in RA and AF Values at Commencement of Concrete Particle Movement

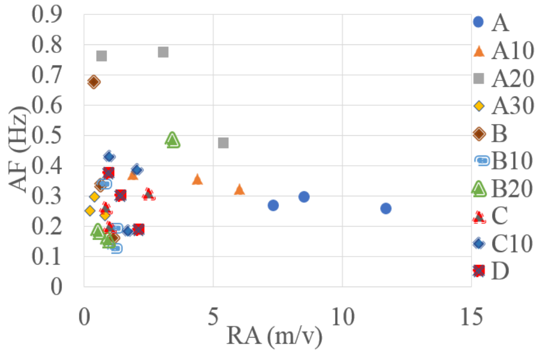



(b) Compressive Strength at Commencement of Concrete Particle Movement

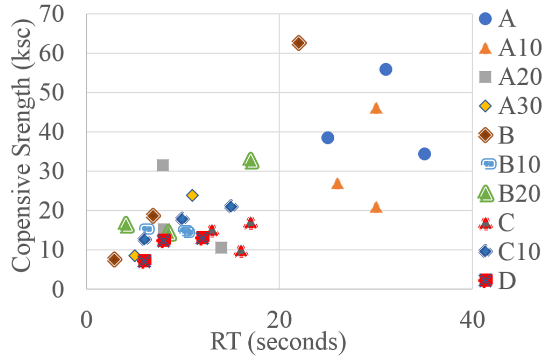



(c) Maximum Compressive Strength and Maximum Number of Revolutions in Concrete Movement

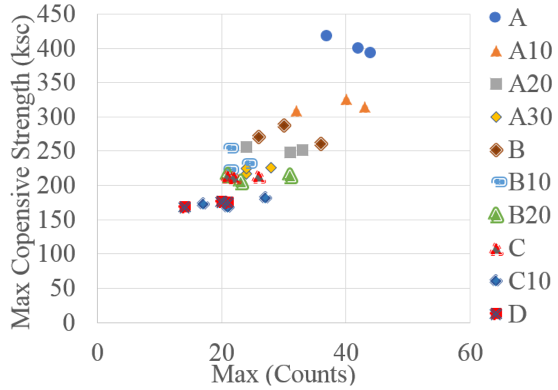
Fig. 10 Results of Measuring Compressive Behavior of Concrete after 14 Days of Water Curing




(a) Changes in RA and AF Values at Commencement of Concrete Particle Movement




(b) Compressive Strength at Commencement of Concrete Particle Movement




(c) Maximum Compressive Strength and Maximum Number of Revolutions in Concrete Movement

Fig. 11 Results of Measuring Compressive Behavior of Concrete after 28 Days of Water Curing

the PW surface may have been the reason for the decreasing count number and RT with increasing the amount of PW. Notably, the greater the amount of PW replacement and the greater the repeated recycle number to the value of RA, RT and count number in similar to the changing of compressive strength. There appeared to be a relationship between the compressive strength of the recycled concrete and the AE parameters; however, this requires further experimentation to elucidate.

The results of this study conformed well with other studies. Using PET bottles as plastic waste for sand replacement in concrete affected the mechanical properties. Concrete containing 10% recycled PET had a compressive strength that met the standard strength requirement [29]. This study also investigated using concrete waste as coarse aggregate in RAC; increasing the amount of round recycled coarse aggregate from concrete waste did not adversely affect the mechanical properties of the prepared concrete.

## 5. CONCLUSIONS

This research focused on the use of recycling aggregates and plastic replacement of fine aggregate. The effects of increasing the PW % and the number of recycle rounds were investigated. The replacement of PW impacted both the compressive strength and the rate of strength development after curing time. Increasing the PW % replacement in RAC had a greater effect on the recycled concrete strength than increasing the number of recycling rounds. For every 10 % of increased PW in the recycled concrete, there was an increasing rate of strength development after 7–14 days on average of 12.29, 11.59, 8.22, and 2.27 % and after 14-28 days on average of 5.37, 5.52, 2.76, and 3.05 % from rounds 1–4, respectively. Increasing the number of recycling rounds increased the rates of strength development after 7–14 days on average by 14.86, 14.88, 8.63, and 8.04 % and after 14–28 days on average by 7.25, 10.36, 2.05, and 3.15 % for 0, 10, 20, and 30 % (v/v) of PW replacement, respectively. The AE testing conducted in this research showed that increasing the PW % of fine aggregate replacement affected the values of RA, RT and AF. The AE testing results provided data that indicated that the engineering properties of recycled concrete were satisfactory for commercial use along with the replacement of fine aggregate with 10 % PW. Based on these research findings, more engineering properties of concrete containing recycled ingredients should be evaluated to ensure that it can be used as an important structural material in the future that can reduce the use of natural aggregates and accelerate PW management.

## 5. ACKNOWLEDGMENTS

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