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File size:	1.11M
Page count:	7
Word count:	4,352
Character count:	22,808
Submission date:	10-Apr-2023 12:39PM (UTC+0700)
Submission ID:	2060304530

Jurnal Teknologi

Full Paper

THE INFLUENCE OF RIVER AND VOLCANIC SAND AS COATINGS ON POLYPROPYLENE WASTE COARSE AGGREGATE TOWARDS CONCRETE COMPRESSIVE STRENGTH

Gandjar Pamudji[a,b]*, Madsuri Satim[a], Mochamad Chalid[c], Heru Purnomo[a]

[a]Civil Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok 16424, West Java, Indonesia
[b]Civil Engineering Department, Faculty of Engineering, Jenderal Soedirman University, Purwokerto, Central Java, Indonesia
[c]Metallurgical and Materials Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok 16424, West Java, Indonesia

Article history
Received
10 August 2019
Received in revised form
20 April 2020
Accepted
30 April 2020
Published online
22 June 2020

*Corresponding author
gandjar.pamudji@unsoed.ac.id

Graphical abstract

Abstract

One of the most important factors used to determine the compressive strength of concrete is its aggregate and matrix adhesion. This study examines the surface properties of polypropylene (PP) waste coarse aggregate (PWCA) to determine the influence of sand. The PWCA was made from the PP waste and different types of coating such as PWCA-R (river sand) and PWCA-V (volcanic sand), with experimental tests conducted on the physical properties of sand and PWCA, while the compressive strength, FESEM and density of polypropylene waste coarse aggregate concrete (PWCAC). Concrete specimens were prepared by replacing natural coarse aggregate with PWCA in percentages of 0%, 25%, 50%, 75%, and 100%, varying the water-cement ratio by 0.3 and 0.42 and using polypropylene (PP) waste coarse aggregate (PWCA-R and PWCA-V) as the coating material. The results showed that fineness modulus (F.M) and water absorption of the river sand was higher compared to volcanic sand. The PWCA-V had higher density and specific gravity compared to PWCA-R. On the other hand, water absorption of the PWCA-V was lower than PWCA-R. The PWCA concrete had density which varies from 1740 kg/m^3 to 2074 kg/m^3. For both, the PWCA concrete compressive strength at 28 days with a 100% replacement ratio was reduced by 43% to 55% compared to the natural coarse aggregate (NCA) concrete with 0.3 and 0.42 water-cement ratios. Also, the structural efficiency of PWCAC decreased with an increase in replacement ratio. River sand adhered to the PWCA surface resulted in a better compressive strength value compared to the volcanic sand.

Keywords: Volcanic sand, River sand, Polypropylene waste coarse aggregate, Compressive strength, Density, FESEM

82:4 (2020) 11–16 | www.jurnalteknologi.utm.my | eISSN 2180–3722 | DOI: https://doi.org/10.11113/jt.v82.14124 |

UTM Jurnal

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One of the most important factors used to determine the compressive strength of concrete is its aggregate and matrix adhesion. This study examines the surface properties of polypropylene (PP) waste coarse aggregate (PWCA) to determine the influence of sand. The PWCA was made from the PP waste and different types of coating such as PWCA-R (river sand) and PWCA-V (volcanic sand), with experimental tests conducted on the physical properties of sand and PWCA, while the compressive strength, FESEM and density of polypropylene waste coarse aggregate concrete (PWCAC). Concrete specimens were prepared by replacing natural coarse aggregate with PWCA in percentages of 0%, 25%, 50%, 75%, and 100%, varying the water-cement ratio by 0.3 and 0.42 and using polypropylene (PP) waste coarse aggregate (PWCA-R and PWCA-V) as the coating material. The results showed that fineness modulus (F.M) and water absorption of the river sand was higher compared to volcanic sand. The PWCA-V had higher density and specific gravity compared to PWCA-R. On the other hand, water absorption of the PWCA-V was lower than PWCA-R. The PWCA concrete had density which varies from 1740 kg/m^3 to 2074 kg/m^3. For both, the PWCA concrete compressive strength at 28 days with a 100% replacement ratio was reduced by 43% to 55% compared to the natural coarse aggregate (NCA) concrete with 0.3 and 0.42 water-cement ratios. Also, the structural efficiency of PWCAC decreased with an increase in replacement ratio. River sand adhered to the PWCA surface resulted in a better compressive strength value compared to the volcanic sand.

Keywords: Volcanic sand, River sand, Polypropylene waste coarse aggregate, Compressive strength, Density, FESEM

1.0 INTRODUCTION

Lightweight aggregate is one of the important elements to reduce the weight of concrete and increase the building's resistance to earthquakes. This is necessary due to the linear dependence of the magnitude of the earthquake load received by a building on its mass. Therefore, it is used due to its significant benefits such as smaller cross-sections of building structural elements, especially in the foundations [1], [2]. Moreover, it is possible to obtain lightweight aggregates naturally, for example, from oil palm shells, pumice, and scoria, or artificially through the sintering process, such as granulated blast furnace slag (GBFS), diatomite, clay, fly ash, shale or slate.

In recent years, using plastic waste as a substitute for natural aggregate in concrete mixes has attracted much attention from researchers, especially due to its ability to reduce the weight of the concrete [3], [4], [5], [6], [7]. Rooms are now also constructed to be more comfortable and have the ability to save energy due to the significant difference between the cooling and heating loads in them [8]. Moreover, lightweight aggregates with plastic material have been reported to have lower water absorption due to the hydrophobic nature of plastics [9].

On the other hand, since the 20th century was discovered, the consumption of plastic has grown substantially all over the world, when it was first developed for industrial use. The many advantages of plastics have caused an increase in its production by plastic industries. This was also attached to its low cost, high strength to weight ratio, is resistant to damage (durable), is easy to work and shape, and has a low density. According to plasticeurope data [10], up to 335 million tons was produced globally in 2016 with Asia ranked first with 50% followed by Europe with 19%, NAFTA 18%, Middle East and Africa 7%, and Latin America with 6%. However, non-reusable plastics have been discovered to be causing environmental problems because they are not easily degraded or decomposed naturally and cannot be used properly. The wastes from these plastics are, therefore, used in concrete mixtures in order to protect the environment from pollution. Thus, this plastic waste becomes a positive potential as a raw material in making lightweight aggregates. This is one of the solutions to manage or recycle plastic waste to produce new materials that will benefit the community in the future. Subsequently, it has benefits from an economic and ecological perspective [3].

Some types of plastic previously used as aggregates in concrete mixtures include high density polyethylene (HDPE) [11], [12], polyethylene terephthalate (PET)[4], [9], [13]–[17], polyvinyl chloride (PVC)[18], [19], polypropylene (PP) [20], and electronic wastes (e-wastes) [21], [22].

Pamudji *et al*. [23] developed lightweight coarse aggregates from HDPE, LDPE, and PP wastes to replace natural coarse aggregates in concrete mixtures. At 28 days, approximately 60% of lower compressive strength was obtained when compared to normal concrete. Similar results were obtained by Mustafa *et al*. through the use of HDPE plastic waste as a substitute. This was associated with the low adhesive or bond strength between the surface of the plastic aggregate and the cement paste due to the aforementioned hydrophobic properties which makes it impossible for the material to absorb water. This further inhibits cement hydration due to limited water movement.

To increase the interaction between cement paste and plastic aggregates to improve the mechanical performance of the concrete, Purnomo *et al*. [20] coated the surface of the coarse aggregate PP developed by Pamudji el al [23] with volcanic sand, Choi *et al*. [15] used raw materials from PET bottles waste and GBFS for making the lightweight aggregate, while Choi *et al*. [4] used PET bottles waste and river sand powder.

This research is part of the coarse aggregate development of plastic waste conducted by Pamudji *et al*. [23] and Purnomo *et al*. [20] to investigate the effect of coating poplypropylene (PP) waste coarse aggregate surface with sand types on concrete performance. In Indonesia, there are two types of sand ordinarily used for making concrete and they include river sand (RS) and volcanic sand (VS). They have different physical properties because of the variation in their origin Volcanic sand is obtained from cooled lava, therefore, it has a sharp surface, and hardness while river sand, in contrast, is soft and has a smooth rounded shape [24].

The two types of sand were used in the study to coating poplypropylene waste aggregate as coarse aggregates, while the river sand were used as fine aggregates. To investigate the influence of sands, aggregate bonding to a matrix in concrete materials, the study wholes perform by varying types of the sands. Furthermore, evaluate the bonding behavior the concrete products were characterized by measuring FESEM to observe the morphology; measuring density to investigate the weight of concrete due to aggregate content; measuring compressive strength to investigate the quality of concrete as an effect of the bonding behavior.

2.0 METHODOLOGY

Materials

Cement, sand, coarse aggregates, water, and admixture were the key materials used to form concrete. However, the cement used was Portland Composite Cement produced in Indonesia and production standards of SNI 15-7064-2014, ASTM C595-13, and EN 197-1:2011 are satisfied.

The concrete constituent consists of the fine aggregate (FA) and coarse aggregate (CA). The FA used in the mix was river sand (RS) cleaned from dirt by washing it first to remove the impurities and later spreading it out for a saturated surface dry condition. Meanwhile, the natural coarse aggregate was a crushed stone with a maximum size of 20 mm while the lightweight coarse aggregates were manufactured from the waste polypropylene according to the following procedure.

The waste PP was cleaned and chopped using a plastic grinding machine to produce shredded plastic with a 16 mm maximum size. The product was later put into a plastic injection machine to be shaped like natural coarse aggregates (NCA) at a melting temperature of 130°C ± 10 °C. After the plastic aggregates were formed, they were removed from the mold, cooled, and referred to as the plain (uncoated) plastic aggregates.

Figure 1 PP waste coarse aggregates: (a) coated plastic aggregate shape with river sand (RS), (b) coated plastic aggregate shape with volcanic sand (VS)

These aggregates were in two sizes, 10 mm and 20 mm, on the longest side and later coated with hot sands from two different sources, RS and VS passed through a No.12 sieve (1.68 mm), using a coating machine. The final of polypropylene (PP) waste coarse aggregate (PWCA) includes two type; coated with river sand (PWCA-R) and coated with volcanic sand (PWCA-V) are shown in Figure 1.

A superplasticizer was used as the admixture material for the 0.3 water-cement ratio to improve the workability of fresh concrete with a specific gravity of 1.18 to 1.2 at 27°C.

Methods

Ten mixes were designed to study the effect of polypropylene waste lightweight coarse aggregate (PWCA) content at 0%, 25%, 50%, 75%, 100%, the water-cement ratio at 0.3 and 0.42, as well as the sand type coating, RS and VS, on the compressive strength and density of concrete. The detailed design of the mixture is presented in Table 1.

The labeling system is designed to clearly show the concrete type. Each type was assigned seven characters. This labeling system includes abbreviations for the variable parameters. The first five letters "PWCAC" represent the polypropylene-waste-coarse-aggregate concrete. The next one letters "V" or "S" represent of sand type, where "V" for volcanic and "R" for the river. The next letter is number "0.30" or "0.42" represents the water-cement ratio.

The physical properties of sand as a fine aggregate in a concrete mixture and a coating material to produce PWCA, as well as those of coarse aggregate PP plastic waste, were tested in the laboratory. The indicators include density, gradation analysis (fine aggregate), fineness modulus (fine aggregate), specific gravity, and water absorption with reference to the applicable testing standards in Indonesia.

The specimens to test for the concrete compressive strength have a cylindrical shape with a 100 mm diameter and 200 mm height. They were produced by casting fresh concrete into a cylindrical mold and compacting it by pricking using twenty-five times round steel rods on each layer up to the required three layers. After the sample became hardened, the mold was opened and the specimen removed. Moreover, the density and compressive strength were tested after a curing period of 28 days according to SNI 03-3402-1990 and SNI 1974-2011.

Table 1 Concrete mix proportion

Content of PWCA	W/C	Cement (kg)	Sand (kg)	NCA (kg)	PWCA (kg)	Water (kg)	SP (kg)
100%	0.3	500	738	0	677	150	7
75%	0.3	500	738	97	508	150	7
50%	0.3	500	738	194	338	150	7
25%	0.3	500	738	291	169	150	7
0%	0.3	500	738	388	0	150	7
100%	0.42	468	657	0	566	195	0
75%	0.42	468	657	246	424	195	0
50%	0.42	468	657	493	283	195	0
25%	0.42	468	657	739	141	195	0
0%	0.42	468	657	986	0	195	0

The experiment was conducted in the structure and materials laboratory of the Civil Engineering Department, Engineering Faculty, Universitas Indonesia.

3.0 RESULTS AND DISCUSSION

Aggregate Properties

Physical Properties of Sand. The results of the sieve analysis conducted on the fine aggregate (RS and VS) are presented in Figures 2 and 3. It shows the grading curve for the river and volcanic sands is within the lower and upper limit required for aggregate from natural source SNI- 03-2834-2000. Moreover, the river sand granules were observed to be in a rather rough zone-2 while volcanic sands were in fine zone-3. This means the river sands have rougher grains compared to volcanic sand based on the fineness modulus values presented in Table 2.

The specific gravity, absorption, and unit weights of both types of sand also had different values as shown in Table 2. It was also discovered that river sand is lighter than volcanic sand based on density and specific gravity and had greater absorption value because the weight of its granules is influenced by the pores contained in them.

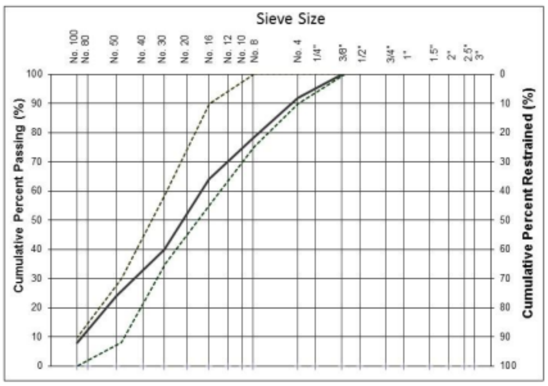


Figure 2 Grading size distribution of river sand

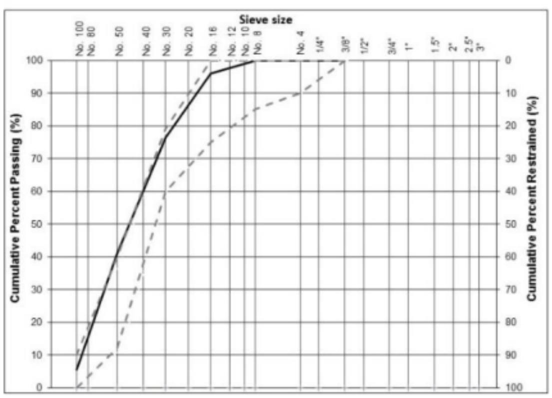


Figure 3 Grading size distribution of volcanic sand

Table 2 Physical properties of fine aggregate

Component	RS	VS
Dry Loose Density (g/cm^3)	1.25	1.62
Specific gravity (SSD)	2.33	2.63
Absorption (%)	3.31	1.47
Fineness modulus	2.94	1.81

Physical Properties of Coarse Aggregate. The physical observations showed the NCA had triangular and pentagonal aggregate shapes according to the aggregate cluster [25]. This was caused by the crushing process of the stone into coarse aggregate sizes. However, the PWCA was found to be round and regular in size as shown in Figures 1a and 1b due to the use of a surface coating process with the sand heated to 150°C and rotated in a circular vacuum mixer machine to have a consistent size. Therefore, the inner part of the PWCA was solid PP while the surface was coated with sand to improve the interface properties with cement mortar and fire resistance.

The results also showed the PWCA and PWCA-V had a density of 511 kg/m^3 and 696 kg/m^3, respectively, classified as lightweight coarse aggregate according to SNI 2461-2014. PWCA-V a water absorption, however, was 2.35%, which is smaller than 4.99% a water absorption of PWCA-R as presented in Table 3. Visually, the surface of PWCA coated with river sand tends to be rougher than those with volcanic sand. This was caused by the rougher grain size of river sand compared to volcanic sand according to the aggregate gradations analysis and fine modulus values shown in Figure 2, Figure 3 and Table 2. This, therefore, means the physical characteristics of the sand affect those of the PWCA formed as described in Table 3. For example, the plastic aggregates coated with river sand had a lighter weight compared to the volcanic sand and this was associated with the space between the grains of sand covering the plastic aggregate surface and the pores determined through the amount of water absorption as presented in Table 3.

Table 3 Physical properties of coarse aggregate

Component	PWCA-R	PWCA-V	Natural Coarse Aggregate
Dry Loose Density (kg/m3)	511	696	1220
Specific gravity (SSD)	1.12	1.22	2.65
Absorption (%)	4.99	2.35	7.82

Physical Properties of Concrete

Density of Concrete. The densities of the hard-concrete samples were measured in dry conditions just before the compression strength test. Moreover, the relationship between the density and the replacement ratio of PWCA compared based on the sand type is shown in Figure 4. The results showed the PWCAC density decreased as the replacement ratio of PWCA was increased when compared to the natural aggregate concrete (NAC). The density of

PWCAC with 100% natural aggregate replacement by PWCA at 0.3 and 0.42 water-cement ratio was found to have reduced by 18% and 28%, respectively with the range in 1600–1775 kg/m^3. However, the density of PWCAC at the FAS 0.3 water-water ratio showed a slight difference for both concrete types, plastic aggregates coated with RS was 1764 kg/m^3 while those with VS was 1740 kg/m^3. Moreover, based on the weight, they were both in the range of lightweight concrete classification according to SNI 2847-2013 and ACI 213-87.

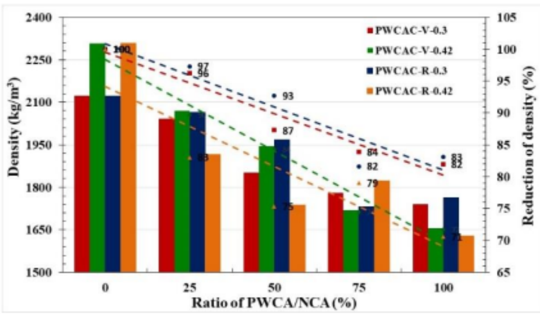
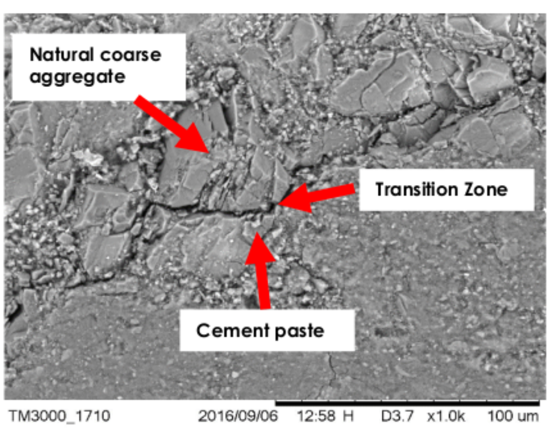
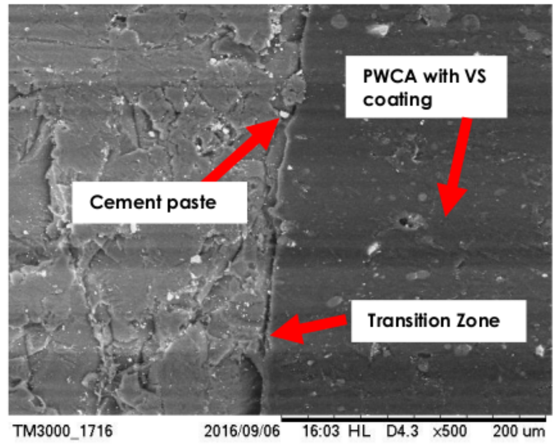


Figure 4 Density variation with w/c ratio for concrete various

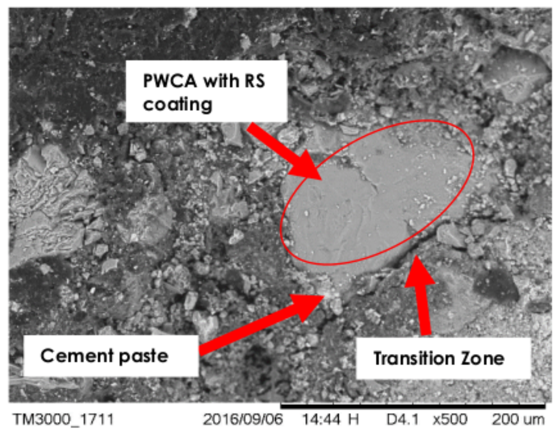
Interfacial Bonding of Cement Paste-coarse Aggregate. Figure 5 shows the transition zone between cement paste and coarse aggregate in the concrete. The interfacial transition zone (ITZ) between cement paste and PWCA-R showed a tendency to have a uniform and smaller gaps compared to natural coarse aggregate because the PWCA-R surface is rougher due to the formation of sand layers in PWCA-R as shown in Figure 5a and Figure 5c. This phenomenon has also occurred between the cement paste and the PWCA-V. Therefore, it means the interlocking properties between the cement paste and the plastic coarse aggregates are better than for natural coarse aggregates.



(a) Transition zone between mortar and NCA



(b) Transition zone between mortar and PWCA-V



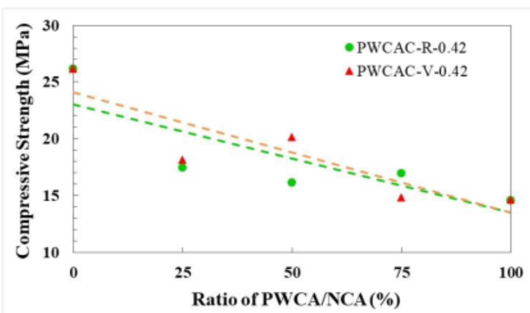
(c) Transition zone between mortar and PWCA-R

Figure 5 Transition zone between mortar and coarse aggregate

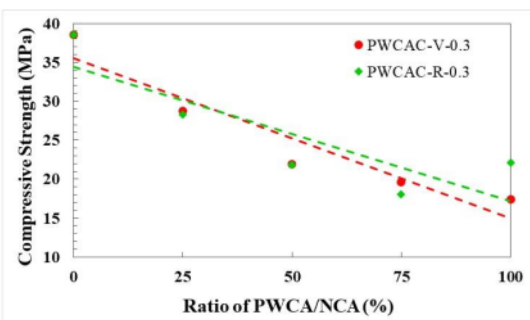
Mechanical Properties of Concrete

According to the results presented in Figure 6, the compressive strength of the concrete was found to be reduced with the increase in the PWCA content. At 100% plastic aggregate, the highest strength was obtained from the specimen containing plastic aggregates coated with RS and at 0.3 water-cement ratios. This was observed to be due to the strong influence of cement paste to bind plastic aggregates that occur at the interfacial transition zone. The paste occupies the void spaces and coats the aggregate surface, therefore, the amount required is determined using these two factors [26].

However, the void spaces of PWCA were influenced by the surface coating process and the type of sand used as the coating material. Based on result physical properties test as shown Table 2, the RS tends to be round, rough, with high sufficient absorption and inability to effectively interlock each other during the coating process, thereby, producing a PWCA with a rougher surface shape and higher sufficient absorption compared to those coated with VS. This, therefore, increased the number of void spaces produced as indicated by the quantity of cement paste on the PWCA and cement paste interface shown in the SEM results of Figures 5b and 5c. A concrete with relatively better working ability was produced where the cement paste is always sufficient to coat the aggregate surface and provide the necessary lubrication. Thus, the amount of water in ITZ is reduced due to reacting with cement, furthermore, it occupies the voids of sand grain attached in the surface of the plastic aggregate which has an impact on reducing the air content in the mix [14], [27]. This attribute has the potential of producing concrete with a strong cement pasta-PWCA interface, allowing improved concrete compressive strength.



(a) Concrete compressive strength with 0.42 w/c ratio



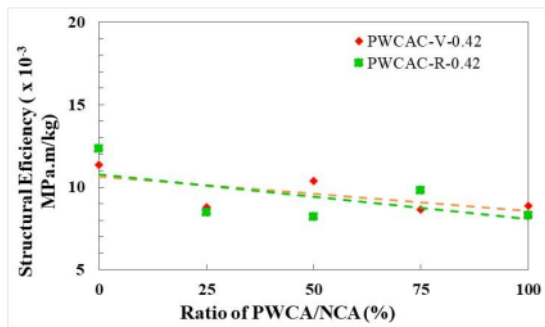
(b) Concrete compressive strength with 0.3 w/c ratio

Figure 6 Variation in concrete compressive strength with w/c ratio and different of the sand coating

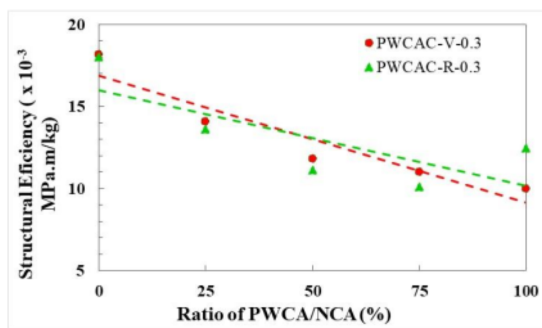
Besides, lightweight concrete containing 100% PWCA with a 0.3 water-cement ratio (W/C) had a compressive strength of 22.13 and 17.39 for PWCAC-R and PWCAC-V respectively, and its more than 17.42 MPa, this means classified as structural lightweight concrete according to the ACI 213-87. Conversely, the concrete with 0.42 W/C involved the substitution of 25% natural coarse aggregate with PWCA.

Structural Efficiency

The relationship between the structural efficiency (compressive strength/density ratio) [15] and the replacement ratio of PWCA at 28-days is shown in Figure 7. The structural efficiency was found to be decreasing as the replacement ratio and water-cement ratio increase. The value obtained for PWCAC-V with a 100% replacement ratio was approximately 45% lower than the control concrete. Moreover, the value for PWCAC-R was obtained 31% lower than for control concrete at the 0.3 W/C. This may be attributed to the influence of PWCA weight and matrix strength.



(a) Structural efficiency with 0.42 w/c ratio



(b) Structural efficiency with 0.3 w/c ratio

Figure 7 Relationship between structural efficiency and replacement ratio of PWCA

4.0 CONCLUSION

This research contributes to the management of wastes and presents a way to recycle PP waste as building construction materials. Moreover, the effect of coating the PWCA materials with different types of sand on the compressive strength of concrete was investigated. From this study, it was found that the density of PWCA-R and PWCA-V was approximately 42% and 57%, respectively, lower than the natural coarse aggregate. The replacement of natural coarse aggregates with PWCA contributes to the reduction of the concrete self-weight. The density of PWCAC-V and PWCAC-R tend to decrease by 18% and 17%, respectively, when compared with the NCA, for mixtures with 0.3 water-to-cement ratios (W/C), and with 100% replacement.

The compressive strength of PWCAC was observed to be decreasing as the PWCA content in the concrete mixture was increased. Moreover, the structural efficiency of PWCAC, where 100% of NCA was replaced by PWCA-V and PWCA-R was approximate 45% and 31%, respectively, lower than NCA concrete. This may be attributed to the influence of PWCA weight and matrix strength

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