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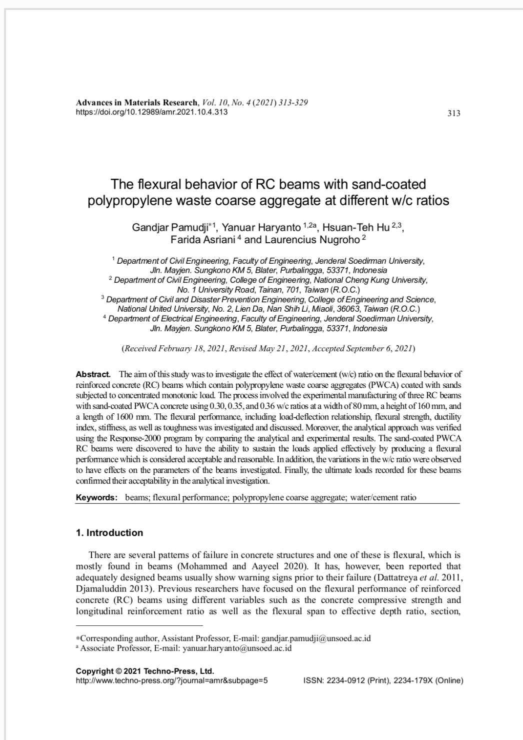

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The flexural behavior of RC beams with sand-coated polypropylene waste coarse aggregate at different w/c ratios

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Keywords: beams; flexural performance; polypropylene coarse aggregate; water/cement ratio

1. Introduction

There are several patterns of failure in concrete structures and one of these is flexural, which is mostly found in beams (Mohammed and Aayeel 2020). It has, however, been reported that adequately designed beams usually show warning signs prior to their failure (Dattatreya *et al.* 2011, Djamaluddin 2013). Previous researchers have focused on the flexural performance of reinforced concrete (RC) beams using different variables such as the concrete compressive strength and longitudinal reinforcement ratio as well as the flexural span to effective depth ratio, section,

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1. Introduction

There are several patterns of failure in concrete structures and one of these is flexural, which is mostly found in beams (Mohammed and Aayeel 2020). It has, however, been reported that adequately designed beams usually show warning signs prior to their failure (Dattatreya *et al.* 2011, Djamaluddin 2013). Previous researchers have focused on the flexural performance of reinforced concrete (RC) beams using different variables such as the concrete compressive strength and longitudinal reinforcement ratio as well as the flexural span to effective depth ratio, section,

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member size, aggregate types, loading types, and other support conditions (Arezoumandi *et al.* 2015, Chaboki *et al.* 2018, Sunayana and Barai 2018, Seara-Paz *et al*. 2018). There is generally an appearance of cracks in RC beams due to the application of excess stress when compared to the concrete's tensile strength. These cracks usually spread quickly up towards or close to the beams' neutral axis and moves progressively to produce flexural cracks which are associated with bending stresses and happen mostly in beams with rectangular configurations.

Plastic has, however, become one of the most widely used products in daily living. It is defined as a synthetic material made from organic polymers and which can be molded into different shapes, either in soft or rigid form. Plastics are applied for several purposes due to their versatility, ease of production, imperviousness nature to water, and relatively low cost. This material is available in different types such as polyethylene terephthalate (PET), polystyrene, light density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC), and others. Global production of plastic has increased significantly in the last 50 years with a total of approximately 359 million metric tons recorded in 2018. Its amazing versatility is believed to be the reason for its annual production growth (Garside 2020). This means plastics are making life easier even though there is a need to think about their disposal system, environmental impact, and other consequences. The non-biodegradable behavior of this material is the main problem which leads to congestion and environmental pollution and this means more advantages are expected from reusing waste plastics in other aspects of daily life. This is necessary in order to protect non-replenishable natural resources and also to reduce environmental pollution.

Some research works have previously studied the use of plastic wastes as fibers in concrete (Marthong 2019, Mazloom and Mirzamohammadi 2019). Others focused on its use as a replacement for aggregate in concretes (Mustafa Al Bakri *et al*. 2011, Saikia and De Brito 2014, Islam *et al.* 2016, Frigione 2010, Kou *et al*. 2009, Haghighatnejad *et al*. 2016, Purnomo *et al*. 2017, Arora and Dave 2013, Lakhsmi and Nagan 2010) and polypropylene was found to have performed better than PET (Islam *et al*. 2015, Mathew *et al*. 2013). Polypropylene is a cheap and plentiful thermoplastic applied in different areas such as to package foods as well as the production of, laboratory equipment, textiles, polymer banknotes, and automotive components. It resists several solvents produced from different chemicals as well as acids and bases and also has the ability to resist fatigue, thereby, leading to its use in the production of several plastic living hinges such as flip-top bottles. This continuous use has, however, led to the availability of a significant amount of this material as solid waste which is currently being used in concretes. Meanwhile, Purnomo *et al.* (2017) was reported to have coated the surface of the coarse aggregate polypropylene developed by Pamudji *et al*. (2012) with volcanic sand in order to enhance the concrete's mechanical performance through an improvement in the interaction between the cement paste and plastic aggregates. The effect of coating the Polypropylene Waste Coarse Aggregate (PWCA) materials with different types of sand on the compressive strength of concrete has also been investigated by Pamudji *et al.* (2020).

The water-cement (w/c) ratio has also been discovered to be playing a significant function in the concrete mix to ensure workability and, subsequently, increase the RC strength (Alawode and Idowu 2011, Isaac 2016). Beygi *et al.* (2013) also experimented to evaluate the parameters of fracture and brittleness in self-compacting concrete (SCC) at different w/c ratios ranging between 0.7 and 0.35 and the findings indicated a linear increase in the fracture toughness, an approximate doubling of the brittleness number, and roughly smoother fracture surface for the concrete as the ratio reduced from 0.7 to 0.35. This was, however, associated with the improvement in the bond strength between the paste and aggregates. Wang *et al*. (2020) also found a significant influence of concrete strength based on the w/c ratio and coarse aggregate on the fracture surface of the concrete. An increment in the w/c ratio was observed to be making the surface of the fracture coarser and the aggregate lower strength was found to have caused the fracture surface of the concrete with limestone to be smoother than those with the normal aggregate at a specific w/c. Moreover, the effect of the w/c ratio on the mechanical and shield attributes of heavyweight magnetite concrete was also evaluated by Lotfi-Omran *et al.* (2019). The findings showed an increment of the w/c ratio from 0.4 to 0.7 led to a reduction in the value of compressive strength for the heavyweight magnetite concrete by 54%, which is from 62 to 28.2 MPa. A reduction trend was also observed in the gamma-ray passing flux as the w/c ratio reduced.

There are several experimental and analytical research on this concept, but most of the results are scattered and the unavailability of data in few cases showed the need for more studies to build more confidence in the use of concrete made with PWCA. Therefore, this research was conducted to determine the effect of the w/c ratio on the flexural behavior of RC beams made with 100% of natural coarse aggregates replaced with sand-coated PWCA (S-PWCA). The application of 100% replacement was, however, due to the findings of Pamudji *et al.* (2020). Therefore, 3 different w/c ratios which are 0.30, 0.35, and 0.36 were used in this research while several parameters including load-deflection relationship, flexural strength, ductility index, stiffness, as well as toughness were investigated and discussed. Finally, the theoretical method was verified using a program which is known as Response-2000 (R2K) in line with the Modified Compression field Theory (MCFT) (Bentz 2000).

2. Experimental work

2.1 Materials

2.1.1 Reinforcement steel

This is involved the application of steel bars with 6 mm and 8 mm diameters for reinforcement as the findings from the tests conducted in line with the ASTM A615 (2018) are indicated in Fig. 1 and Table 1.

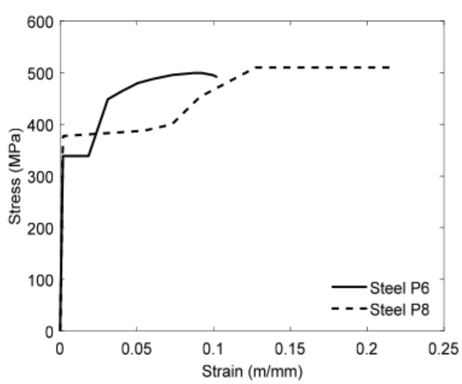


Fig. 1 Tensile stress-strain curves of reinforcement steel

Table 1 Reinforcement steel bars

Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
6	338	499	10.23
8	365	510	21.82

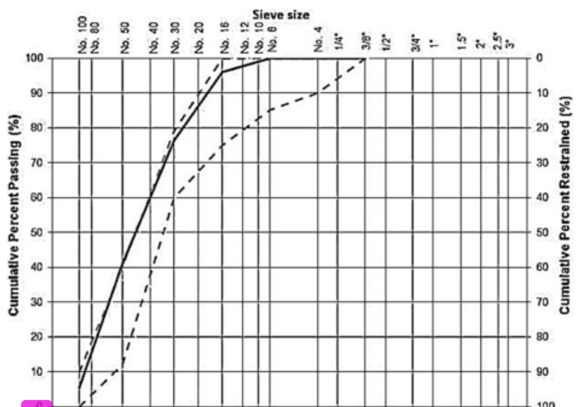


Fig. 2 Grading size distribution of sand (Pamudji *et al*. 2020)

Table 2 The physical properties of fine aggregates (Pamudji *et al*. 2020)

Properties	Test results
Dry loose density (g/cm^3)	1.62
Specific gravity (SSD)	2.63
Absorption (%)	1.47
Fineness modulus	1.81

2.1.2 Sand

The fine aggregates used in this study were volcanic sand and the sieve analysis and physical property tests conducted on this material in line with SNI-03-2834-2000 specifications (2000) are presented in Fig. 2 and Table 2. The grading curve for the sand was found to be within the lower and upper limits required for aggregate from the natural source while the sand granules were observed to be in fine zone-3.

2.1.3 Polypropylene waste coarse aggregate (PWCA)

The coarse aggregates were manufactured from waste polypropylene and the process involved cleaning and chopping the waste PP with a plastic grinding machine to produce shredded plastic with a maximum size of 16 mm, the products were later placed into a plastic injection machine to be shaped like natural coarse aggregates (NCA) at a melting temperature of 130°C ± 10°C, after which they were removed from the mold, cooled, and referred to as the plain or uncoated plastic

Fig. 3 Polypropylene waste coarse aggregate coated with sand

Table 3 The physical properties of S-PWCA (Pamudji *et al.* 2020)

Properties	Test results
Dry loose density (g/cm^3)	0.70
Specific gravity (SSD)	1.22
Absorption (%)	2.35

aggregates. These aggregates were in two sizes, 10 mm and 20 mm, on the longest side and later coated with hot sands which were passed through a No. 12 sieve or 1.68 mm using a coating machine. The final sand-coated polypropylene waste coarse aggregates (S-PWCA) are presented in Fig. 3 while their physical properties are listed in Table 3.

2.1.4 Cement and superplasticizer

Portland Composite Cement which was manufactured in Indonesia based on SNI 15-7064-2014, ASTM C595-13, and EN 197-1:2011 standard was used in this research while the superplasticizer (SP) was applied as the admixture material for all w/c ratio in order to enhance the fresh concrete workability with 1.18 to 1.2 specific gravity at 27°C.

2.2 Concrete

The mixture proportions applied in this research are presented in Table 4 while their designation symbols are displayed in Fig. 4. The coarse aggregate volume in the mixture was 100% replaced with sand-coated PWCA. The targeted density for the concrete mix was between 1600–1775 kg/m^3 at 0.3, 0.35, and 0.36 w/c ratio variations and expected strength of 20 MPa at 28 days of curing with a 7 kg/m^3 and 5 kg/m^3 superplasticizer. It should be noted that the mixtures can be classified as lightweight concrete based on the density and according to SNI 2847-2013 and ACI 213-87.

The materials were mixed by first pouring 40% of water with SP into the mixer followed by the addition of dry S-PWCA particles and the solution was mixed continuously for approximately 2 minutes to ensure full wetting. This was followed by the addition of solid materials as well as the gradual addition of the remaining 60% of the water into the mixer during the process of mixing to achieve uniformity and even distribution of S-PWCA particles in the mixture. The content was

Table 4 The quantity of materials in the mix proportions

Mix design	w/c ratio	Cement (kg/m^3)	Sand (kg/m^3)	S-PWCA (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
B-PP-0.30	0.30	500	738	388	150	7
B-PP-0.35	0.35	500	823	386	175	5
B-PP-0.36	0.36	500	823	386	180	5

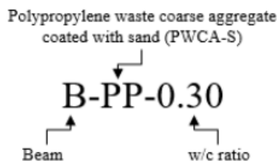


Fig. 4 The designation symbols for the concrete mix

mixed continuously for another 5 minutes after which the slump and fresh densities were evaluated.

The three samples of RC beams were produced through the use of 3 different concrete mixes with varying w/c ratios and cast using molds after the process of mixing. Moreover, standard specimens were used to determine different parameters with slump test used to indicate the smoothness and workability during the process of casting and conducted for all the mixtures according to SNI-1972-2008 code (2008). The compressive strength was determined after curing for 28 days using six cylinders with a diameter of 150 mm and a height of 300 mm. It is important to note that the same dimension was to evaluate the concrete's density in line with SNI-2847-2013 (2013).

The compressive strength results for the mixtures are presented in Table 5 using w/c ratio as the important variable while superplasticizer was applied to recover part of the workability and compressive strength lost due to the application of S-PWCA. It was discovered that there is a reduction in the compressive strength due to the increment in the w/c ratio as shown in Table 5. Moreover, there was an increment in the pores of the cement paste, especially at the interfacial transition zone (ITZ), as the w/c ratio increased and this led to a reduction in the quality of ITZ, compressive strength and the concrete fracture mode also changed from through to around the aggregates. This trend is the same as the trend recorded for normal concrete (Kharita *et al.* 2010, Petersson 1980, Rao 2001, Fernandes *et al*. 2005), heavyweight concrete (Yang *et al*. 2014, Lotfi-Omran *et al.* 2019), self-compacting concrete (Nikbin *et al*. 2014, Topcu and Uygunoglu 2010, Beygi *et al.* 2013), and high-performance concrete (Bharatkumar *et al.* 2005). Moreover, all the

Table 5 Slump value, concrete density, and compressive strength

Concrete type	Slump (cm)	Density (kg/m^3)	Compressive strength (MPa)
B-PP-0.30	6	1954	21.88
B-PP-0.35	10	1840	18.48
B-PP-0.36	14	1915	18.06

concretes are applicable for structural purposes since they all satisfied the 17 MPa minimum compressive strength required by ACI code ACI 318M-14 (2014).

2.3 Geometric features of RC beam specimens

The symbols designated for the mixes and RC beam specimens are presented in Fig. 4 and the use of 0.30 w/c is represented by B-PP-0.30, 0.35 by B-PP-0.35, and 0.36 by B-PP-0.36 with 100% of the coarse aggregate volume replaced with S-PWCA. The flexural behavior of these concrete mixes, especially the strength and factors affecting their values was studied using simply supported RC beams designed to have a width of 80 mm, a height of 160 mm, and length of 1600 mm. The detailed information on the design of the RC beams is presented in Table 6 while their dimensions and reinforcement are indicated in Fig. 5.

Table 6 RC beams design

Beams designation	w/c ratio	Longitudinal reinforcement		Transverse reinforcement
		Tension	Compression	
B-PP-0.30	0.30	2Ø8	2Ø8	Ø6-150
B-PP-0.35	0.35	2Ø8	2Ø8	Ø6-150
B-PP-0.36	0.36	2Ø8	2Ø8	Ø6-150

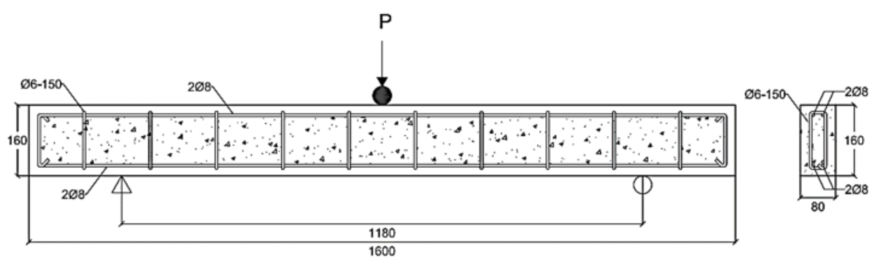


Fig. 5 The dimensions and reinforcement of RC beams

Fig. 6 Three-point bending test for RC beam

2.4 Testing procedures for the RC beam specimens

The test setup for the specimens is displayed in Fig. 6. The process involved conducting a three-point bending test on the RC beams simply supported using steel rods and subjected to a concentrated load to ensure an accurate physical representation.

A 2000 kN-capacity universal testing machine was used to determine the flexural strength at 1.5 kN/s load rate while the mid-span deflection was recorded with the corresponding load applied using the Linear Variable Differential Transformer (LVDT) placed at the specimen bottom. The first significant crack was observed up to the moment of failure to determine the maximum load and deflection.

3. Experimental results and discussion

The three RC beams with sand-coated PWCA were produced at different w/c ratios and tested experimentally. There was an evaluation of the load-deflection relationships with respect to the RC beams mid-span, flexural strength, ductility index, stiffness, and toughness after which the results from the experiment and those from the analysis were compared.

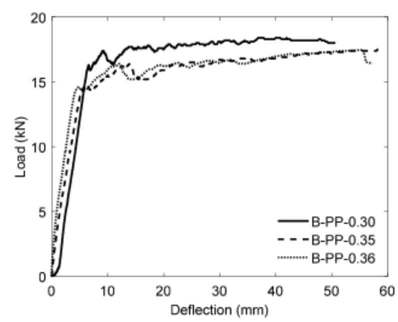


Fig. 7 Load-deflection curves for all specimens

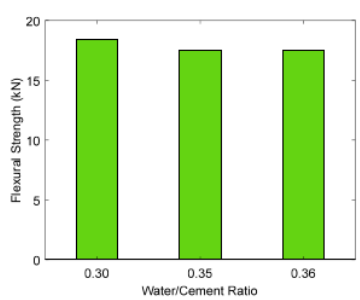
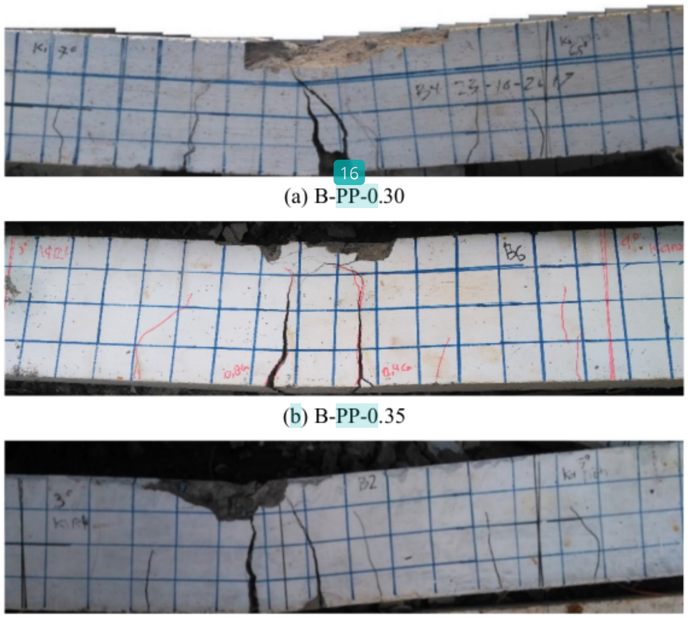


Fig. 8 Flexural strength vs w/c ratio



(a) B-PP-0.30

(b) B-PP-0.35

(c) B-PP-0.36

Fig. 9 Failure modes for the beams

3.1 RC beams Load-deflection relationship

The relationship between the load applied and mid-span deflection presented in Fig. 7 showed a similar graph pattern for the w/c ratios. The peak values of the B-PP-0.36 beam were observed to exhibit lower maximum flexural strength than B-PP-0.35 and B-PP-0.30, respectively. The maximum deflection values were also observed to remain within the approximated limits. Meanwhile, the graph of flexural strength against w/c ratio plotted in Fig. 8 showed the specimen with a 0.35 and 0.36 w/c ratio had a value which is 4.89% and 5.04% lower than the specimen with 0.30 w/c ratio. The cracking pattern and cracks at failure were also recorded as presented in Fig. 9 and the beams were discovered to have experienced a flexural failure. From this discussion it is evident that the increase in w/c ratio of the beams led to a reduction in flexural strength. Therefore, it is concluded that an increment in the w/c ratio affects the flexural strength of beams by causing early failure even though it has the ability to improve workability (Oad *et al.* 2019). According to Oad *et al.* (2019), it is important to note that the reduction in flexural strength is not affected by the type of coarse aggregate used.

3.2 Ductility of RC beams

The concept of ductility has been described to be a material or member's ability to sustain deformation beyond the elastic limit and maintain an appropriate capacity to carry load up to the

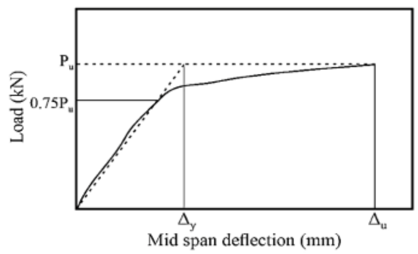


Fig. 10 Typical load-mid span deflection for RC beams

Table 7 Ductility index value of the beams

Beams	Δ_u	Δ_y	$\mu\Delta$
B-PP-0.30	40.835	7.404	5.515
B-PP-0.35	58.309	6.208	9.392
B-PP-0.36	55.628	4.846	11.479

moment of total failure. One of the best ways to measure deformation in an RC beam is through its curvature but the deflection is also used as an alternative due to the ease with which it can be measured.

The most significant factor requiring consideration in evaluating ductility is the sustainable maximum deflection for material or member before failure (Pam *et al.* 2001). The ductility index is usually calculated using Eq. (1) with Δ_u used to represent the deflection at the ultimate load while Δ_y is the deflection at the yielding load, which is also the theoretical yield point deflection of an equivalent elasto-plastic system.

$$\mu\Delta = \frac{\Delta_u}{\Delta_y} \tag{1}$$

The secant stiffness is considered equal to its equivalent elastic stiffness such that the load is 75% before reaching the ultimate load (Haryanto *et al.* 2021), as indicated in Fig. 10.

The ductility index calculated in Table 7 showed the beams made with 0.30 and 0.35 w/c ratio reduced by 51.95% and 18.18% respectively, when compared with the beam of 0.36 w/c ratio. This is in line with the previous report of Siddique and Rouf (2006) that concrete compressive strength had an important effect on beams' ductility index. An increment in the compressive strength of flexural members such as the beam usually leads to a reduction in the member's ductility index while other properties are kept the same (Sunayana and Barai 2018, Alasadi *et al.* 2020). It was discovered in the present study that the reduction in the w/c ratio of the mixtures enhanced the concrete compressive strength and this caused a reduction in the ductility index.

3.3 Stiffness of RC beams

The calculation of stiffness in line with the ASTM C1018-97 (1998) requires dividing the deflection of the beam at 45% of the ultimate load to the corresponding load and the values

Table 8 Stiffness value of the beams

Beams	45% P_u (kN)	Δ at 45% P_u (mm)	Stiffness (kN/mm)
B-PP-0.30	8.28	3.72	2.23
B-PP-0.35	7.88	2.57	3.07
B-PP-0.36	7.86	1.84	4.28

Table 9 Toughness value for the beams

Beams	Toughness (kN.mm)
B-PP-0.30	833.157
B-PP-0.35	907.591
B-PP-0.36	914.102

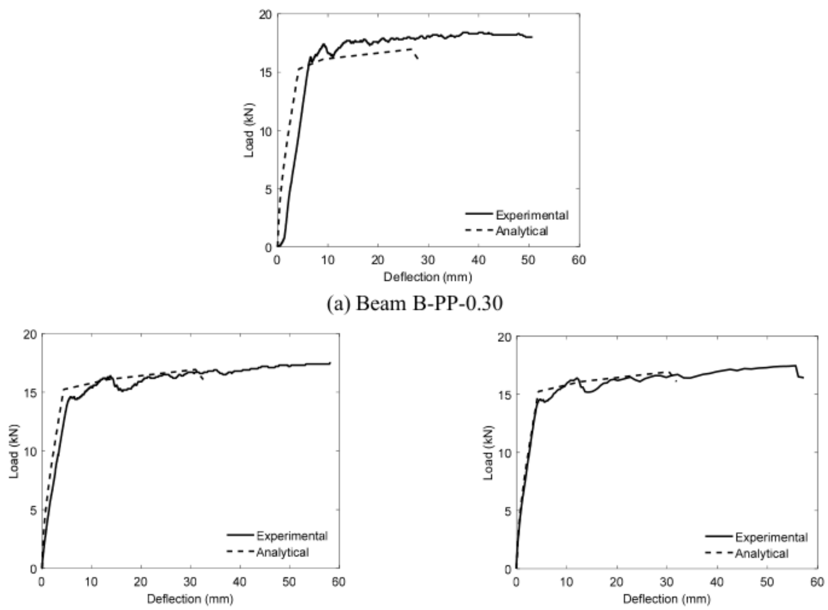
obtained in this study are indicated in Table 8. It was discovered that there was an increase in the stiffness due to the increment in the w/c ratio, thereby causing a reduction in the compressive strength of the concrete. This is, however, observed to be different from previous findings by Ashour (2000) and Yang *et al.* (2018). The increment recorded in the stiffness was associated with the insignificant deflection at 45% of the beams' ultimate load due to the fact that it rests on the load-deflection curve's elastic part before the first crack occurred. The value recorded was discovered to be in the beams' transformation region which is from elasticity to plasticity. The increment in the w/c ratio led to a proportional increment in the values of the stiffness which were recorded to be 37.67% and 91.93% for B-PP-0.35 and B-PP-0.36, respectively when compared with the B-PP-0.30.

3.4 Toughness of RC beams

Toughness is defined as a specimen's ability to absorb energy and is also explained to be the quantity of energy needed to break a specimen. It is considered an indicator of structural integrity like strength and ductility due to its ability to sustain the system unity when placed under unusual physical loads. Several processes which are considered complex effect RC element toughness such as the fracture mechanics of crack initiation and propagation as well as the elastic and plastic deformation (Nielsen and Cao 2010, Godat *et al*. 2010). The calculation of toughness is usually through the load-deflection curve area and the values in Table 9 were calculated through the use of the trapezoidal rule. Toughness is affected by several parameters such as the concrete compressive strength (Hanoon *et al*. 2017) and it was observed to have reduced due to increment in compressive strength of the concrete based on the reduction of the w/c ratio. The beams made with 0.30 and 0.35 w/c ratio had a toughness reduction estimated at 9.72% and 0.71% respectively when compared with those produced using 0.36 w/c ratio.

4. Analytical investigation

An analytical investigation was conducted using a program designed through the Modified Compression Field Theory (MCFT) which is known as Response-2000 (R2K) (Bentz 2000). This



(a) Beam B-PP-0.30

(b) Beam B-PP-0.35

(c) Beam B-PP-0.36

Fig. 11 Comparison between experimental and analytical

Table 10 Comparison between experimental and analytical

Beams	P_u (kN)		Ratio
	Experimental	Analytical	$P_{u,Exp}/P_{u,An}$
B-PP-0.30	18.40	16.96	1.09
B-PP-0.35	17.50	16.94	1.03
B-PP-0.36	17.47	16.93	1.03

method has been reported to be reliable, quick, and with an excellent ability to predict experimental behavior (Lam *et al.* 2011, Metwally 2012, Suryanto *et al*. 2016, Huang *et al*. 2019).

The three beams tested were modeled and analyzed to ensure the analytical model's validation and accuracy after which the data predicted by the R2K program and those obtained from the experiment were compared. The experimental and predicted values for the load versus mid-span deflection at all stages of loading are indicated in Fig. 11 while the ultimate load values and the ratio of the two methods are compared in Table 10.

Fig. 11 shows the predicted results generally replicate the experimental responses closely and this is indicated by the prediction of an initial linear-elastic, transitional nonlinear, and reasonably linear responses up to the peak load for each beam. This alignment in the findings was considered impressive due to the complexness of the actual response starting from the moment the new concrete cracks were formed and pre-existing ones were propagated which further decreased the overall stiffness of the beam. It is, however, important to note that the response near the peak was not reproduced efficiently with the analytical predictions specifically observed to have the tendency to under-estimate the ductility of the beams. Nevertheless, the Normalized Mean Square Error (NMSE) for the prediction of flexural strength was found to be 0.003 and this is considered acceptable as required from the design point of view.

5. Conclusions

The present study focused on the flexural behavior of RC beams designed using polypropylene waste coarse aggregate (PWCA) coated with sand at different w/c ratios and subjected to concentrated monotonic load. The conclusions drawn from the experiments and theoretical analysis conducted are as follows:

- Concrete with sand-coated polypropylene waste coarse aggregate (S-PWCA) was classified as lightweight and considered useful for structural purposes.
- An increment in the w/c ratio from 0.30 to 0.35 was discovered to have reduced the compressive strength by 15.50% as observed from 21.88 to 18.48 MPa and an increment from 0.30 to 0.36 caused a 17.42% reduction as indicated with a decrease from 21.88 to 18.06 MPa.
- The flexural strength of the beams produced using 0.35 and 0.36 w/c ratio was 4.89% and 5.04% respectively lower when compared with the beam of 0.30 w/c ratio and the failure mode was observed to be flexural.
- The ductility index of the beams made with 0.30 and 0.35 w/c ratio had 51.95% and 18.18% reduction respectively when compared with 0.36 w/c ratio.
- An increment in the w/c ratio was discovered to have caused a relative increase in stiffness by 37.67% and 91.93% for beams made with 0.35 and 0.36 w/c respectively in comparison to those produced using a 0.30 w/c ratio. This increment was, however, related to the small deflection at 45% of the ultimate load.
- The toughness of the beams made with 0.30 and 0.35 w/c ratio reduced by 9.72% and 0.71% respectively when compared with 0.36 w/c ratio.
- The predicted responses generally replicate the experimental responses closely but it is important to note that the response near the peak was not reproduced effectively with the analytical predictions specifically observed to have the tendency to under-estimate the ductility of the beams.
- The Normalized Mean Square Error (NMSE) for the prediction of flexural strength was found to be 0.003 and this is considered acceptable as required from the design point of view.
- The findings of this study have to be seen in light of a limitation that the number of the beam specimens need to be increased in the future work.

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Conflict of interest

The authors declare no potential conflict of interest.

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