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The Flexural Behavior of RC Beams with Sand-coated Polypropylene Waste Coarse Aggregate at Different w/c Ratios

Author(s)

Gandjar Pamudji, Yanuar Haryanto, Hsuan-Teh Hu, Farida Asriani, Laurencius Nugroho

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

Abstract. ~~This~~ The aim of this study ~~aimed~~ was to investigate the effect of water/cement ratio on the flexural behavior of reinforced concrete (RC) beams ~~containing~~ which contain polypropylene waste coarse ~~aggregate~~ aggregates (PWCA) coated with ~~sand~~ sands subjected to concentrated monotonic load. ~~Three~~ The process involved the experimental manufacturing of three RC beams ~~having~~ with sand-coated PWCA concrete ~~were manufactured experimentally~~ using 0.30, 0.~~35~~ 35, and 0.36 water-cement ~~ratio. The beam dimensions were~~ ratios at a width of 80 ~~mm width~~mm, a height of 160 ~~mm height~~mm, and a length of 1600 ~~mm length~~mm. The flexural performance including load-deflection relationship, flexural strength, ductility index, ~~the~~ stiffness, as well as toughness ~~were~~ was investigated and discussed. Moreover, the analytical approach was verified using the Response-2000 ~~program,~~ program by comparing the analytical ~~results with those of the~~ and experimental ~~tests~~results. The ~~results show that~~ sand-coated PWCA RC beams ~~can effectively~~ were discovered to have the ability to sustain the loads applied ~~loads with~~ effectively by producing a flexural performance which is considered acceptable and ~~reasonable flexural performance~~reasonable. In addition, ~~different~~ the variations in the w/c ratio ~~affect~~ were observed to have effects on the parameters ~~investigated on sand-coated PWCA RC beams~~of the beams investigated. ~~Finnaly~~Finally, ~~sand-coated PWCA RC~~ the ultimate loads recorded for these beams ~~were found to be acceptable within~~ confirmed their acceptability in the analytical ~~investigation in terms of their ultimate load~~investigation.

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

1. Introduction

~~Different failure patterns~~ There are ~~observed in concrete structures. Flexural failure is a common type~~ several patterns of failure in concrete structures and one of these is flexural which is mostly found in beams (Mohammed and Aayeel 2020). ~~If properly designed~~It has, however, been reported that adequately designed beams ~~exhibit clear~~ usually show warning signs ~~before they fail~~ prior to their failure (Dattatreya *et al.* 2011, Djamaluddin 2013). ~~Numerous studies~~ Previous researchers have ~~been conducted~~ focused on the flexural performance of reinforced concrete (RC) ~~beams. A number of variables,~~ beams using different variables such as ~~concrete~~ the compressive strength and longitudinal reinforcement ~~ratio, affect the flexural behavior~~ ratios of ~~RC beams. In addition,~~ concrete as well as the ~~ratio of~~ flexural span to effective ~~depth~~depth ratio, section, ~~and the size of the member~~member size, aggregate ~~type~~types, ~~type of loading~~loading types, and other support conditions ~~all have an impact on flexural strength~~ (Arezoumandi *et al.* 2018, Chaboki *et al.* 2018, Sunayana and Barai 2018, Seara-Paz *et. al.* 2018). ~~Generally,~~ There is generally an appearance of cracks ~~appear~~ in RC beams due to the application of excess stress when ~~applied stress exceeds~~ compared to the concrete's tensile ~~strength of concrete~~strength. These cracks usually spread ~~rapidly upward to~~ quickly up towards or ~~near~~ close to the beams' neutral axis ~~of the~~

~~RC beams, which~~ and moves ~~upwards with progressive cracking. These~~ progressively to produce flexural cracks which are ~~classified as flexural cracks, that occur due to~~ associated with bending ~~stresses, particularly~~ stresses and happen mostly in beams with rectangular ~~beams~~configurations.

~~On the other hand~~Plastic has, however, ~~plastic is becoming~~ become one of the most widely used products in ~~our day to day life~~daily living. It ~~can be~~ is defined as a synthetic material made from organic polymers and which can be molded into ~~various~~ different shapes either in soft or rigid form. ~~Because of its~~ Plastics are applied for several purposes due to their versatility, ease of production, impervious nature to ~~water~~ water, and relatively low ~~cost its being used for wide range of purposes~~cost. ~~There are various~~ This material is available in different types ~~of plastics are available, like~~ such as polyethylene terephthalate (PET), polystyrene, light density polyethylene (LDPE), ~~high~~ high-density polyethylene (HDPE), polypropylene (PP), polyvinyl chloride (PVC~~) etc~~), and others. ~~In the last 50 years, global~~ Global production of plastic has increased ~~to huge extent. In 2018,~~ significantly in the ~~production~~ last 50 years with a total of ~~plastics totaled around~~ approximately 359 million metric tons ~~worldwide~~recorded in 2018. ~~The incredible~~ Its amazing versatility ~~of this group of materials accounts~~ is believed to be the reason for ~~the continued growth in~~ its annual production ~~year after year~~ growth (Garside 2020). ~~So surely it has made our~~ This means plastics are making life ~~much~~ easier ~~but we also must~~ even though there is a need to think about ~~its~~ their disposal system, environmental ~~impact~~ impact, and other consequences. ~~Non~~The non-biodegradable behavior of this material is the main problem ~~with plastic materials~~ which leads to congestion and environmental pollution ~~of the environment. Hence, it will be advantageous if these plastic wastes can be used~~ and this means more advantages are expected from reusing waste plastics in other aspects of ~~our~~ daily life. ~~It will help~~ This is necessary in order to ~~save~~ protect non-replenishable natural resources ~~that are not replenished~~ and ~~decrease the~~ also to reduce environmental pollution.

Some research works ~~were~~ have previously ~~conducted where~~ studied the use of plastic wastes ~~were used~~ as fibers in concrete (Marthong 2019, Mazloom and Mirzamohammadi 2019). ~~Another study were previously performed where plastic wastes were used~~ Others focused on its use as a replacement for aggregate in ~~concrete~~ 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~~). It is evident that~~) and polypropylene ~~performs~~ was found to have performed better ~~as a replacement of aggregate in concrete compare to~~ than PET (Islam *et al.* 2015, Mathew *et al.* 2013). Polypropylene is a cheap and plentiful thermoplastic ~~used~~ applied in ~~a wide variety of applications including food packaging~~different areas such as to package foods as well as the production of, ~~textiles,~~ laboratory equipment, ~~automotive components~~textiles, ~~and~~ polymer banknotes~~. It is generally resistant to most of the chemical solvents~~, ~~bases~~ and ~~acids~~automotive components. It ~~shows very good resistance~~ resists several solvents produced from different chemicals as well as acids and bases and also has the ability to resist fatigue, ~~and thus~~thereby, ~~most~~ leading to its use in the production of several plastic living ~~hinges,~~ hinges such as flip-top bottles. This continuous use has, ~~are made from this material. Because~~ however, led to the availability of ~~its wide application it is also turn out in~~ a significant amount of this material as solid waste ~~material~~which is currently being used in concretes. ~~To increase the interaction between cement paste and plastic aggregates to improve the mechanical performance of the concrete~~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. Moreover,~~ 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 ~~was~~ has also been investigated by Pamudji *et al.* (2020). ~~On the other hand,~~ The water-cement (w/c) ratio ~~plays~~ has also been discovered to be playing a ~~vital role~~ significant function in the concrete mix to ensure ~~the~~ workability ~~which in turn ensures~~ and, subsequently, increase the ~~proper~~ RC strength ~~of reinforced concrete~~ (Alawode and Idowu 2011, Isaac 2016). Beygi *et al.* (2013) ~~conducted experimental work~~ also experimented to evaluate the parameters of fracture ~~parameters~~ and brittleness ~~of~~ in self-~~compacticeng~~ compacting concrete (SCC) ~~with various~~ at different w/c ratios ~~from~~ ranging between 0.7 ~~to 0.35. Test results showed that with decrease of w/c ratio from 0.7 to 0.~~and 0.35 and the findings indicated a linear increase in ~~SCC,~~ the fracture ~~toughness increases linearly~~toughness, an approximate doubling of the brittleness ~~number is approximately doubled~~number, and ~~the~~ roughly smoother fracture surface ~~of~~ for the concrete ~~is roughly smoother~~as the ratio reduced from 0.7 to 0.35. This was, however, ~~which can be attributed to~~ associated with the improvement in the ~~improved~~ bond strength between the ~~aggregates~~ paste and ~~the paste~~aggregates. ~~Moreover,~~ Wang *et al.* (2020) ~~concluded that the fracture surface~~ also found a significant influence of ~~the~~ concrete ~~was greatly affected by the~~ strength ~~of~~ based on the ~~concrete, as determined by w/c,~~ w/c ratio and coarse aggregate on the ~~type~~ fracture surface of ~~coarse aggregate~~the concrete. ~~With an increase~~ An increment in ~~w/c,~~ the w/c was observed to be making the surface of the fracture ~~surface became coarser. Owing to~~ coarser and the aggregate lower strength ~~of the aggregate,~~ was found to have caused the fracture surface of the concrete with ~~the~~ limestone ~~aggregate was~~ to be smoother than ~~that of~~ those with the ~~concrete containing~~ normal aggregate ~~for~~ at a ~~given~~ specific w/c. ~~Lofti-Omran *et al.* (2019) assessed~~ Moreover, the effect of the w/c ratio on the mechanical and ~~shielding characteristics~~ shield attributes of heavyweight magnetite ~~concrete, and~~ concrete was also evaluated by Lofti-Omran *et al.* (2019). The findings showed an increment of the ~~results exhibited that with increasing~~ w/c ratio from 0.4 to 0.~~7,~~7 led to a reduction in the value of compressive strength ~~value of~~ for the heavyweight magnetite concrete ~~decreases~~ by 54% which is from 62 to 28.2 ~~MPa (54% reduction)~~MPa. ~~Furthermore,~~ A reduction trend was also observed in the ~~passing flux of~~ gamma-ray ~~decreases with~~ passing flux as the ~~reduction of~~ w/c ~~ratio~~ratio reduced.

~~The~~ There are several experimental and analytical research ~~remains active~~ on ~~the subject matter,~~ this concept but ~~the scatter~~ most of the results ~~and, in a few cases,~~ are scattered and the unavailability of ~~data, proves that~~ data in few cases showed the need for more ~~research is required~~ studies to build more confidence ~~for~~ in the use of concrete made with PWCA. ~~This motivated the current research. This paper presents~~ Therefore, this research was conducted to determine the effect of the w/c ratio on the flexural behavior of RC beams made with 100% ~~replacement~~ of natural coarse aggregates replaced with sand-coated PWCA (S-PWCA). ~~Selection~~ The application of 100% replacement ~~is based on~~ was, however, due to the ~~outcome~~ findings of ~~the study conducted by~~ Pamudji *et al.* (2020). ~~To achieve the proposed task~~Therefore, ~~three~~ 3 different ~~water~~ water-cement ratios ~~i.e.~~ which are 0.30, 0.~~35~~ 35, and 0.36 were used ~~to study the effect of w/c ratio on the flexural behavior of RC beams made with S-PWCA. Several~~ in this research while several parameters including load-deflection relationship, flexural strength, ductility index, ~~the~~ stiffness, as well as toughness were investigated and discussed. Finally, the theoretical method was verified using a program ~~designed based on~~ which is known as Response-2000 (R2K) in line with the Modified Compression field Theory (MCFT~~) which is known as Response-2000 (R2K~~) (Bentz 2000).

2. Experimental work

2.1 Materials

2.1.1 Reinforcement steel

~~Reinforcement steel bars~~ This is involved the application of steels with ~~diameters of~~ 6 mm and 8 mm ~~were used. The test results are presented according to~~ diameters for reinforcement as the findings from the tests conducted in line with the ASTM A615 (2018~~), as shown~~) are indicated in Fig. 1 and Table 1.

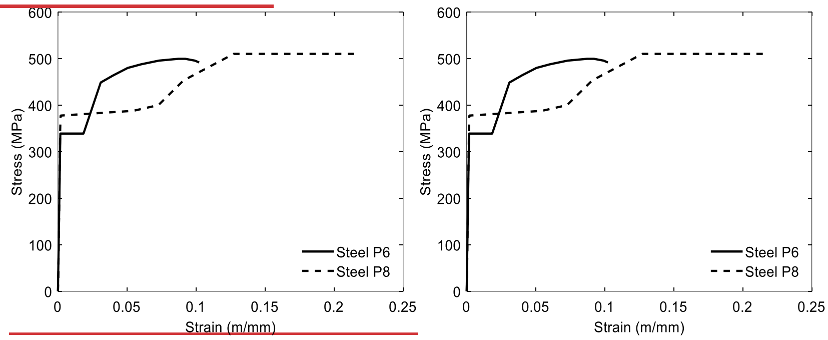


Fig. 1 Tensile stress-strain curves of reinforcement steel

Table ~~1~~ 1: Reinforcement steel ~~bars test result~~bars

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

2.1.2 Sand

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

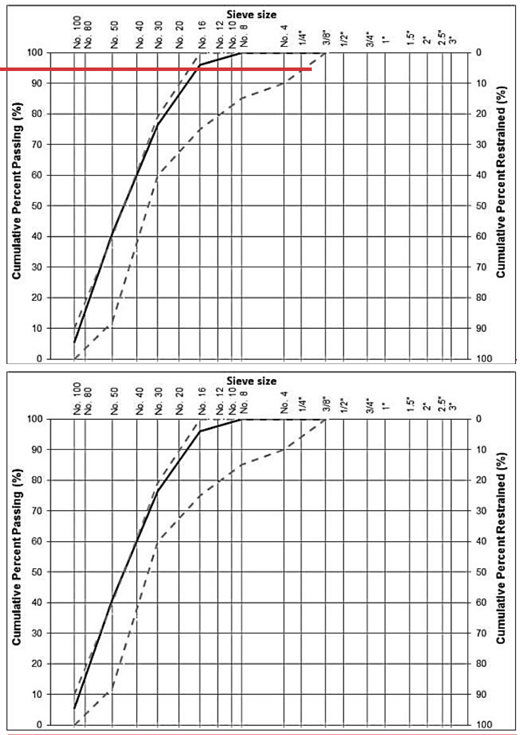


Fig. 2 Grading size distribution of sand (Pamudji *et al.* 2020)

Table 2 2: The Physical properties of fine aggregate aggregates (Pamudji *et al.* 2020)

Properties	Test results
Dry loose denstiy density (g/cm3)	1.62
Specific gravity (SSD)	2.63
Absorption (%)	1.47
Fineness modulus	1.81

2.1.3 Polypropylene waste coarse aggregate (PWCA)

The coarse aggregates were manufactured from the waste polypropylene according to and the following procedure; process involved cleaning and chopping the waste PP was cleaned and chopped using with a plastic grinding machine to produce shredded plastic with a 16 mm maximum sizesize of 16 mm, the product was products were later put placed 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,~~ which they were removed from the mold, cooled, and referred to as the plain ~~(uncoated)~~ or uncoated plastic 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),~~ mm using a coating machine. The final ~~of~~ sand-coated polypropylene waste coarse ~~aggregate~~ aggregates (S-PWCA) are ~~shown~~ presented in Fig. 3.

Fig. 3 Polypropylene waste coarse aggregate coated with sand

2.1.3 Cement and superplasticizer

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

2.2 Concrete

The ~~details of the~~ mixture proportions ~~used~~ applied in this ~~study~~ research are ~~listed~~ presented in Table ~~3, and Fig.~~ 3 ~~displays the applied~~ while their designation ~~symbols~~symbols are displayed in Fig. 3. The ~~mixtures comprised replacing 100% of the~~ coarse aggregate volume in the mixture was 100% replaced with sand-coated PWCA. The ~~mix had a target concrete~~ targeted density ~~with~~ for the ~~range in~~ concrete mix was between 1600–1775 kg/~~m^3, three w/c ratio of~~ m^3 at 0.3, 0.~~35~~ 35, and 0.~~36,~~ 36 w/c ratio variations and ~~an~~ 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 ~~based on the density,~~ the mixtures can be classified as lightweight concrete based on the density and according to SNI 2847-2013 and ACI 213-87.

Table 3 ~~Materials~~ The quantity of materials in the mix proportions

Mix design	w/c ratio	Cement (kg/m^3)	Sand (kg/m^3)	PWCA-S (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

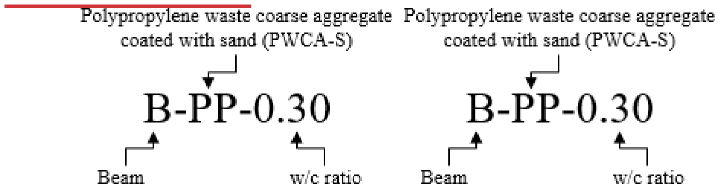


Fig. 3 Concrete mixes The designation symbolssymbols for the concrete mix

The following sequence was used in the mixing of materials: firstly, materials were mixed by first pouring 40% of water with SP was poured inside into the mixer followed by the mixer, then addition of dry S-PWCA particles were added, and mixing continued the solution was mixed continuously for about approximately 2 min minutes to ensure a full wetting with water and superplasticizerwetting. Next, This was followed by the addition of solid materials were poured into as well as the mixer and gradual addition of the remaining 60% of the water was added gradually while into the mixer during the process of mixing was in progress to obtain a uniform mixture achieve uniformity and even distribution of S-PWCA particlesparticles in the mixture. The mixing continued content was mixed continuously for another 5 min, and then minutes after which the slump and fresh densities were measuredevaluated.

Three The three samples of RC beams were poured using three produced through the use of 3 different concrete mixes, each mixes with a different varying w/c ratio. After ratios and cast using molds after the end process of the concrete mixing processmixing. Moreover, the standard specimens were cast using molds. Standard test specimens were selected for testing various parameters. A used to determine different parameters with slump test is an indicator of workability and used to indicate the smoothness and workability during casting. This test was the process of casting and conducted for all the mixtures in line with the code of according to SNI-1972-20082008 code. Six The compressive strength was determined after curing for 28 days using six cylinders with a diameter of 150 mm diameter and a height of 300 mm height were used mm. It is important to determine note that the compressive strength after 28 days of curing. Cylinders of these dimensions were also used same dimension was to determine evaluate the concrete's density of the concrete (in line with SNI-2847-2013).

Table 4 shows the results of the The compressive strength tests results for all concrete mixtures. The key variable used for the mixtures was that of the are presented in Table 4 using w/c ratio. In addition, in these mixtures, ration as the important variable while superplasticizer were used was applied to regain some recover part of the lost workability and compressive strength and workability, reducing lost due to the loss resulting from the use application of PWCA-S. The It was discovered that there is a reduction in the compressive strength reduced as due to the increment in the w/c ratio in the mixtures increased, as illustrated shown in Table 4. The amount of pores Moreover, there was an increment in the pores of the cement paste, particularly in especially at the interfacial transition zone (ITZ), increases with increasing as the w/c ratio. This leads ratio increased and this led to a reduction in the drop quality of ITZ qualityITZ, reduction of f_c and change of the mode of concrete fracture mode also changed from through to around the aggregates. Similar trends were observed This trend is the same as the trend recorded for normal concrete (Kharita *et al.* 2010, Petersson 1980, Appa Rao 2001, Fernandes *et al.* 2005), heavyweight concrete (Yang et al. 2014, Lofti-Omran et al. (2019), self-compacting concrete (Nikbin *et al.* 2014, Topcu and Uygunoglu 2010, Beygi *et al.* 2013), and high high-performance concrte concrete (Bharatkumar *et al.* 2015). FinallyTherefore, based on all the concretes are applicable for structural purposes since they all satisfied the 17 MPa minimum compressive strength required by ACI code ACI 318M-14 (2014), which advises a minimum compressive strength of 17 MPa, all these types of concrete can be used for structural purposes.

Table 4 Concrete density and compressive strength

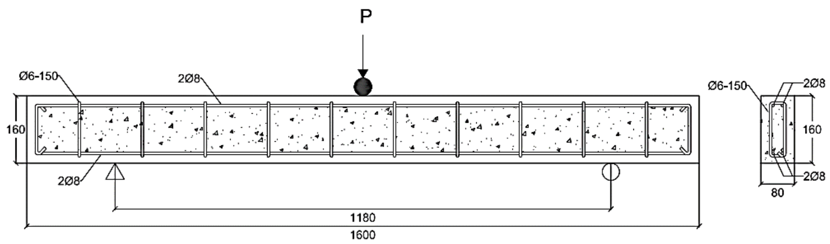
Concrete type	Density (kg/m^3)	Compressive strength (MPa)
B-PP-0.30	1954	21.88
B-PP-0.35	1840	18.48
B-PP-0.36	1915	18.06

2.3 Geometric features of RC beam specimens

Fig. 3 shows the designation The symbols designated for the mixes and also for RC beam specimens. The different mixtures comprised specimens are presented in Fig 3 and the use of w/c 0.30 (w/c is represented by B-PP-0.30), 0.35 (by B-PP-0.35), and (0.36 by B-PP-0.35) 36 with 100% replacement of the coarse aggregate volume by replaced with S-PWCA. Three The flexural behavior of these concrete mixes, especially the strength, and factors affecting their values was studied using 3 simply supported RC beams with dimensions designed to have a width of 80 mm width × 160 mm mm, height × 1600 mm length were used to study the flexural behaviorof 160 mm, and especially the flexural strength, length of different concrete mixes and the factors that affect these values1600 mm. Table 5 shows the details of The detailed information on the design of the RC beams with relevant parameters. Fig. 4 presents the details of the is presented in Table 5 while their dimensions and reinforcement of the RC beamsare indicated in Fig. 5.

Table 5 Detail of RC beams design

Beams designation	w/c ratio	Longitudinal reinforcement		Transverse reinforcement
		Ratios	Details	
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



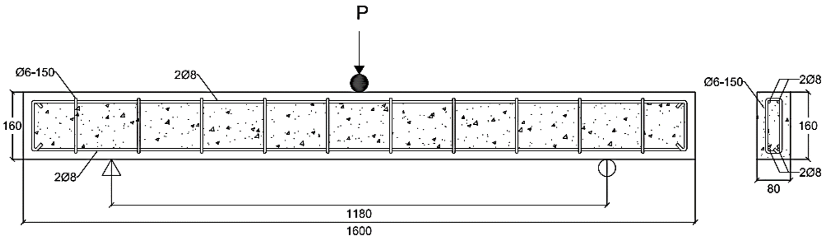


Fig. 4 ~~Details~~ The dimensions and reinforcement of RC beams~~, dimensions and reinforcement~~

2.4 Testing procedures ~~of~~ for the RC beam specimens

The test setup for the specimens is displayed in Fig. ~~6 displays the test setup~~6. ~~A~~ The process involved conducting a three-point bending test ~~was carried out~~ on the RC beams simply supported ~~RC beams, which were supported~~ using steel rods and subjected to a linear load ~~for~~ to ensure an accurate physical ~~representation of the test~~representation. ~~The flexural strength of the RC beams was tested using a~~ A 2000 kN-capacity universal testing machine ~~with a capacity of 2000 kN~~ was used to determine the flexural strength at ~~a load rate of~~ 1.5 kN/~~s. The~~s load rate while the mid-span deflection was recorded with the corresponding load applied using the Linear Variable Differential Transformer (LVDT) ~~was set up~~ placed at the ~~bottom of the~~ specimen ~~to record the mid-span deflection of the beam. For all beams, the mid-span deflection value and the corresponding applied load were recorded~~bottom. The first ~~major~~ significant crack was ~~monitored until~~ observed up to the moment of failure ~~occurred, and~~ to determine the maximum load ~~as well as~~ and deflection~~, were determined~~.

Fig. 6 Three points pending test for RC beam

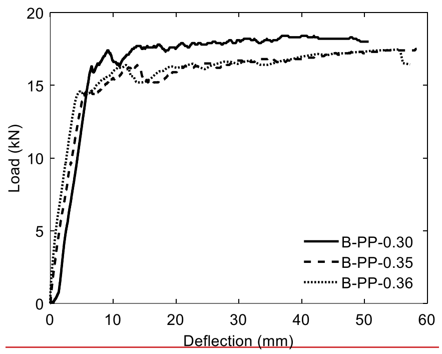
3. Experimental results and discussion

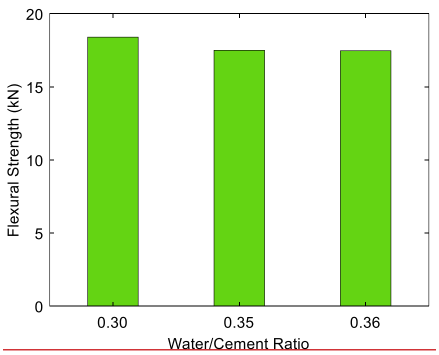
~~Three~~ The three RC beams ~~containing~~ with sand-coated PWCA ~~with~~ were produced at different w/c ~~ratio were manufactured~~ ratios and ~~experimentally tested~~tested experimentally. ~~The~~ There was an evaluation of the load-deflection relationships ~~according~~ with respect to the RC beams mid-~~span of the RC beams~~span, flexural strength, ductility index, ~~the~~ stiffness, and toughness ~~were~~

~~evaluated. A comparison was then conducted between experimental~~ after which the results from the experiment and ~~analytical results~~those from the analysis were compared.

3.1 RC beams Load-deflection ~~relationship of RC beams~~relationship

The relationship between the ~~applied~~ load applied and ~~the~~ mid-span deflection ~~is shown~~ presented in Fig~~. 7~~. ~~It is observed that the pattern of the graphs remained~~ 7 showed a similar ~~within~~ graph pattern for the w/c ~~ratio~~ratios. ~~Peak~~ The peak values of the B-PP-0.36 beam ~~exhibited~~ were observed to exhibit lower maximum flexural strength than B-PP-0.35 and B-PP-0.~~30 beams~~30, ~~respectively. The~~ respectively and a similar trend ~~of flexural strength is observed in both B-PP-0.35 and B-PP-0.30 beams~~was also discovered for the others. ~~Maximum~~ The maximum deflection values ~~of deflection remained~~ were also observed to remain within the ~~limits of approximate maximum deflection~~approximated limits. ~~Flexural~~ Meanwhile, the graph of flexural strength ~~vs~~ against w/c ratio ~~is~~ plotted in Figure ~~8. It is observed that the flexural strength of the beams in comparison to~~ 8 showed the ~~beam of~~ specimen with a 0.30 w/c ratio had a value which is 4.89% and 5.04% lower ~~for beams made with~~ than 0.35 and 0.36 ~~w/c ratio~~ respectively. ~~Cracking~~ The cracking pattern and cracks at failure were also recorded as presented in Figure ~~9. It is clearly observed that~~ 9 and the ~~failure mode of the~~ beams ~~is~~ were discovered to have experienced a flexural ~~failure. From~~ failure and this ~~discussion it is evident that~~ means the increase in w/c ratio ~~leads~~ of the beams led to a reduction in flexural ~~strength of the beams~~strength. Therefore, it is concluded that ~~although increase~~ an increment in the w/c ratio ~~improves~~ affects the ~~workability of concrete, it affects~~ flexural strength ~~leading to~~ of beams by causing early failure ~~of~~ even though it has the ~~beams~~ ability to improve workability (Oad *et al.* 2019). ~~Moreover,~~ According to Oad *et al.* (2019~~) stated~~), it is ~~worth noting~~ important to note that the reduction in flexural strength is ~~independent of~~ not affected by the type of coarse ~~aggregate~~aggregate used.





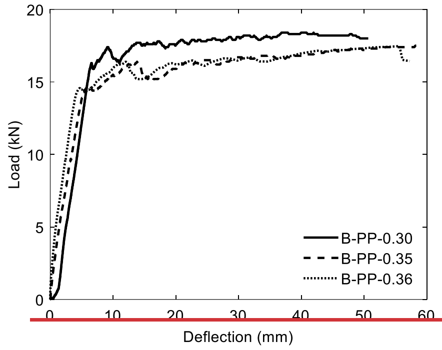


Fig. 7 Load-deflection curves for all specimens

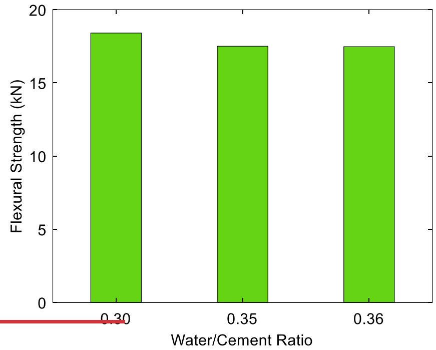
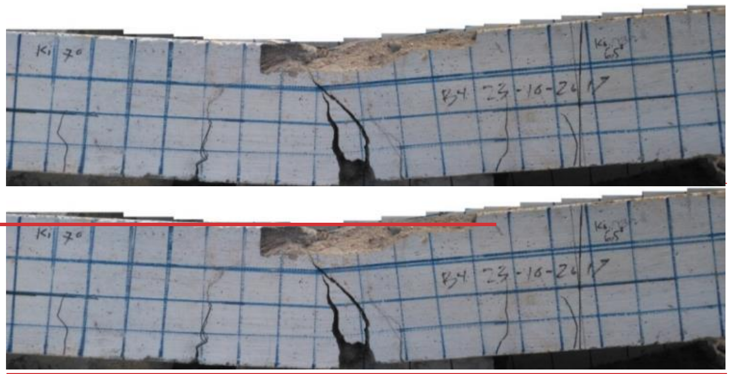
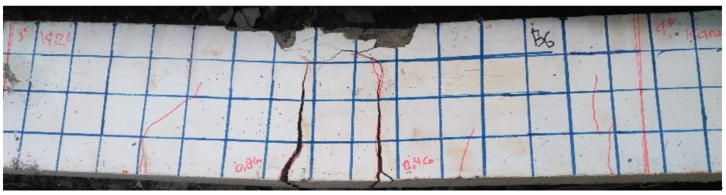


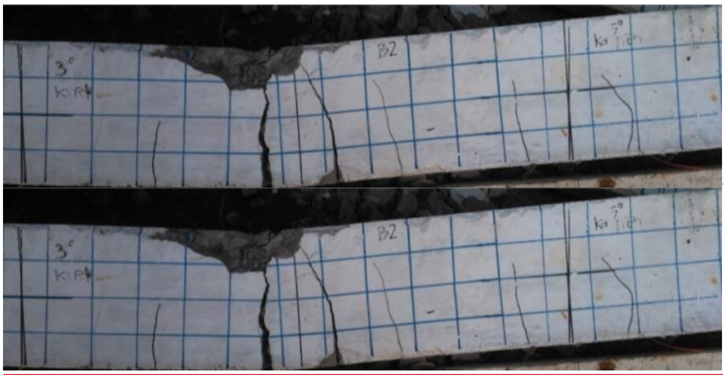
Fig. 8 Flexural strength vs w/c ratio



(a) B-PP-0.30



(b) B-PP-0.35

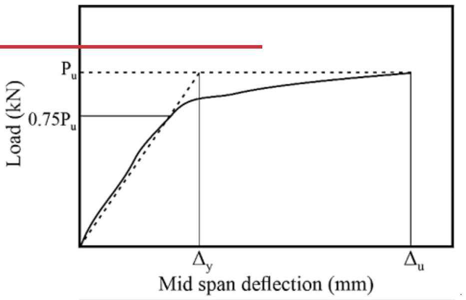


(c) B-PP-0.36

Fig. 9 Failure modes ~~of~~ for the beams

3.2 Ductility of RC beams

~~Ductility is defined as the ability of~~ The concept of ductility has been described to be a ~~material/member~~ material or member’s ability to sustain deformation beyond the elastic limit ~~while maintaining a reasonable load carrying~~ and maintain an appropriate capacity ~~until~~ to carry load up to the moment of total failure. ~~In~~ One of the ~~ease of~~ best ways to measure deformation in an RC ~~beam, the deformation most appropriate for this purpose~~ beam is ~~the~~ through its curvature ~~of the beam. As an alternative,~~ but the deflection ~~of~~ is also used as an alternative due to the ~~beam,~~ ease with which ~~is generally easier to measure, may also~~ it can be ~~used~~measured.



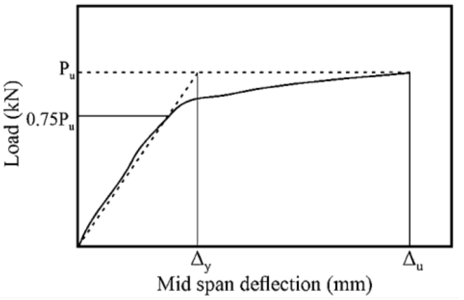


Fig. 10 Typical load-mid span deflection for RC beams

When The most significant factor requiring consideration in the process of evaluating ductility, the most important parameter to be considered ductility is the sustainable maximum deflection that the material/for material or member can sustain prior to before failure (Pam *et al.* 2001). Calculation of the . The ductility index is as shown in usually calculated using Equation (1), where) with Δ_u is used to represent the deflection at the ultimate load and while Δ_y is the deflection at the yielding load. The deflection at the yielding load which is explained to be deflection of also the theoretical yield point deflection of an equivalent elasto-plastic system with the system. The secant stiffness being is considered to be equal to its equivalent elastic stiffness such that the load is 75% before reaching the ultimate load (Haryanto *et al.* 2021),) as shown indicated in Fig. Figure 10.

$$\mu\Delta = \Delta_u / \Delta_y \quad \mu\Delta = \Delta_u / \Delta_y \qquad (1)$$

Field Code Changed

The ductility index is calculated in this study as presented in Table 6. It is observed that 6 showed the ductility index of the beams made with 0.30 and 0.35 w/c ratio shows a reduction of reduced by 51.95% and 18.18%, respectively, in comparison to the beam of 0.36 w/c ratio% respectively when compared with 0.36. As previously reported by This is in line with the previous report of Siddique and Rouf (2006), the) that concrete compressive strength has a significant had an important effect on beams' ductility index. An increment in the ductility index compressive strength of the beams. For flexural members such as beam, the increase beam usually leads to a reduction in concrete compressive strength decreases the member's ductility index of the member

~~if~~ while other ~~beam~~ properties are kept the same (Sunayana and Barai 2018, Alasadai *et al.* 2020). ~~In this study, as~~ It was discovered in the present study that the reduction in the w/c ratio ~~in~~ of the mixtures ~~decreased~~ enhanced the concrete compressive strength ~~enhanced, led to~~ and this caused a reduction in the ductility index.

Table 6 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

3.3 Stiffness of RC beams

~~According to~~ The calculation of stiffness in line with the ASTM C 1018–97 (1998~~), stiffness is calculated by~~) requires dividing the ~~beam~~ deflection of the beam at 45% of the ultimate load to the corresponding ~~load. The stiffness~~ load and the values ~~for all beams~~ obtained in this study are ~~presented~~ indicated in Table 7. ~~In contrast with~~ 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 stiffness of the beams in this study increases with the increase in w/c ratio that led to the decrease in concrete compressive strength~~. The ~~increase~~ increment recorded in the stiffness ~~is related to~~ was associated with the ~~small~~ insignificant deflection at 45% of the beams' ultimate load ~~in~~ due to the ~~beams, because~~ fact that it ~~lies~~ rests on the ~~elastic part of the~~ load-deflection ~~curve,~~ curve's elastic part before ~~occurrence of~~ the first ~~crack~~crack occurred. ~~This~~ The value recorded was discovered to be in the beams' transformation region ~~(~~which is from elasticity to plasticity~~) in the beams~~. ~~An increase~~ The increment in the w/c ratio ~~causes~~ led to a ~~relative increase~~ proportional increment in ~~stiffness~~ the values of the stiffness which were recorded to be 37.67% and 91.93% for ~~beam~~ B-PP-0.35 and B-PP-0.36, ~~respectively, in comparison~~ respectively when compared with ~~beam~~ the B-PP-0.30.

Table 7 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

3.4 Toughness of RC beams

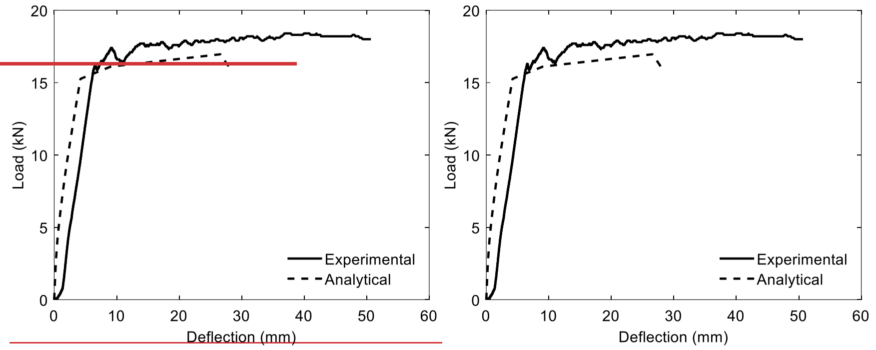
Toughness ~~refers to the~~ is defined as a sample's ability ~~of the sample~~ to absorb ~~energy, otherwise defined as~~ energy and is also explained to be the ~~amount~~ quantity of energy ~~required~~ needed to break ~~the~~ a sample. ~~Similarly to structural strength and ductility, toughness can be~~ It is considered ~~indicative~~ an indicator of structural ~~integrity, toughness is also considered~~ integrity like strength and ductility due to ~~maintain the unity of~~ its ability to sustain the system unity when ~~subjected to~~ placed under unusual physical loads. ~~Various~~ Several processes which are considered complex ~~processes comprise the~~ have RC element toughness ~~of the RC element, such~~ as observed in the fracture mechanics of crack initiation and ~~propagation,~~ propagation as well as the elastic and plastic deformation (Nielsen and Cao 2010, Godat *et al.* 2010). ~~Toughness~~ The calculation of toughness is ~~expressed by the area of~~ usually through the load-deflection ~~curve. The areas under~~ curve area and the ~~curves are calculated~~ values in Table 8 ~~using~~ were calculated through the use of the trapezoidal rule. ~~Different~~ Toughness is affected by several parameters ~~can affect the toughness including~~ such as the concrete compressive strength (Hanoon *et al.* 2016~~). In this study, toughness decreased as the w/c ratio decreased that led~~) and it was observed to ~~the increase~~ have reduced due to increment in compressive strength of the concrete ~~compressive strength. It is observed that~~ based on the ~~toughness~~ reduction of the w/c ratio. The beams made with 0.30 and 0.35 w/c ratio ~~shows~~ had a ~~decrease of~~ toughness reduction estimated at 9.72% and 0.71~~%, respectively, in comparison to the beam of~~% respectively when compared with those produced using 0.36 w/c ratio.

Table 8 Toughness value ~~of~~ for the beams

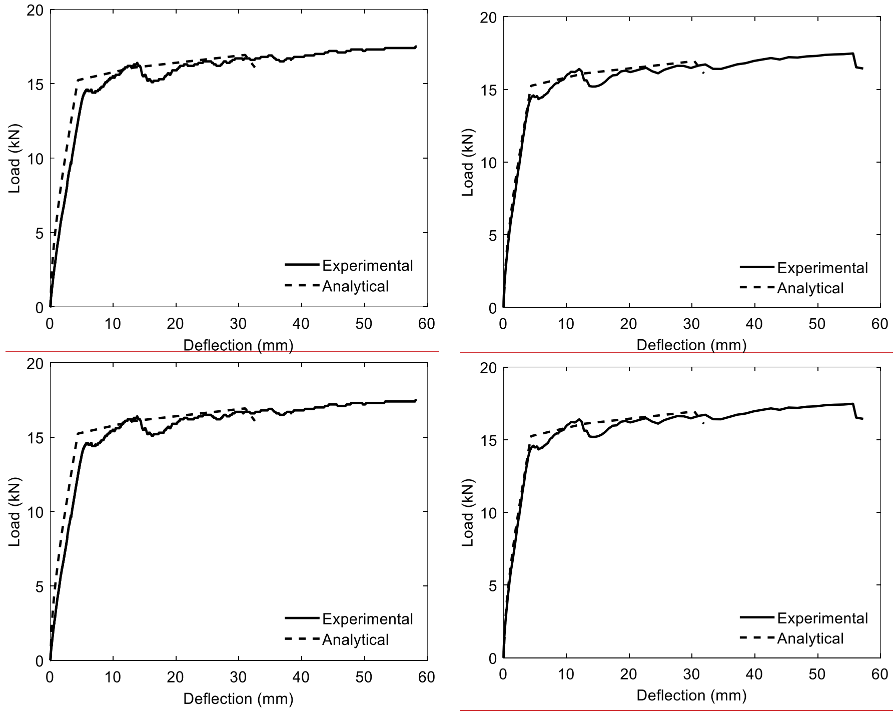
Beams	Toughness (kN.mm)
B-PP-0.30	833.157
B-PP-0.35	907.591
B-PP-0.36	914.102

4. Analytical investigation

An analytical investigation was conducted using a program designed ~~based on~~ through the Modified Compression Field Theory (MCFT) which is known as Response-2000 (R2K) (Bentz 2000). This method has been reported to be reliable, quick, and with an excellent ability to predict experimental ~~behaviour~~ behavior (Lam, Wilson, and Lumantarna 2011; Metwally 2012; Suryanto, Morgan, and Han 2016; Huang *et al.* 2019; Haryanto *et al.* 2021). The three beams tested were ~~modelled~~ modeled and ~~analysed~~ 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 ~~results~~ at all stages of loading are indicated in Figure 11 while the ultimate ~~attained~~ load values and the ratio of the two methods are compared in Table 9.



(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 9 ~~Results comparison~~ 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

Figure 11 shows the predicted ~~responses~~ results generally replicate the experimental responses closely and this is indicated by the prediction ~~of each~~ of ~~the beams to have~~ an initial linear-elastic, ~~a~~ transitional nonlinear, and reasonably linear responses up to the peak ~~load~~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 ~~well~~ 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 (NSM) 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 ~~current work has presented a~~ present study ~~of~~ focused on the flexural behavior of RC beams ~~containing~~ designed using polypropylene waste coarse aggregate (PWCA) coated with sand at ~~various~~ different w/c ~~ratio~~ ratios and subjected to concentrated monotonic load. The ~~following~~ conclusions ~~have been found according to~~ drawn from the ~~experimental~~ experiments and theoretical ~~results of the RC beam tests~~analysis conducted are as follows:

- ~~The concrete~~ Concrete with sand-coated polypropylene waste coarse aggregate (S-PWCA) ~~in this study can be~~ was classified as lightweight ~~concrete~~ and ~~can be used~~ considered useful for structural ~~purpose~~purposes.
- ~~With increasing~~ An increment in the w/c ratio from 0.30 to 0.~~35,~~ 35 was discovered to have reduced the compressive strength ~~value of concrete decreases~~ by 54% as observed from 21.88 to 18.48 MPa ~~(15.54% reduction). Moreover, with increasing w/c ratio~~ and an increment from 0.30 to 0.~~36, the compressive strength value of concrete decreases~~ 36 caused a 17.46 reduction as indicated with a decrease from 21.88 to 18.06 ~~MPa (17.46% reduction).~~MPa.
- ~~It was detected that that the~~ The flexural strength of the beams ~~in comparison to the beam of 0.30~~ produced using 0.35 and 0.36 w/c ratio was is 4.89% and 5.04% respectively lower ~~for beams made~~ when compared with 0.~~35~~ 30 and ~~0.36 w/c ratio respectively. It was also clearly observed that~~ the failure mode ~~of the beams is flexural failure~~was observed to be flexural.

- The ductility index of the beams made with 0.30 and 0.35 w/c ratio ~~shows a reduction of~~ had 51.95% and 18.18~~%, respectively, in comparison to the beam of~~ % reduction respectively when compared with 0.36 w/c ratio.
- An ~~increase~~ increment in the w/c ratio ~~causes~~ was discovered to have caused a relative increase in stiffness ~~of~~ by 37.67% and 91.93% for beams made with 0.35 and 0.36 w/~~c, respectively,~~ c respectively in comparison to ~~the beam of~~ those produced using a 0.30 w/c ratio. ~~The increase in stiffness is~~ This increment was, however, related to the small deflection at 45% of the ultimate ~~load in the beams~~load.
- ~~It was found that the~~ The toughness of the beams made with 0.30 and 0.35 w/c ratio ~~shows a decrease of~~ reduced by 9.72% and 0.71~~%, respectively, in comparison to the beam of~~ % respectively when compared with 0.36 w/c ratio.
- The predicted responses generally replicate the experimental responses ~~closely. However,~~ closely but it ~~should be noted~~ is important to note that the response near the peak was not reproduced ~~well~~ effectively with the analytical predictions specifically observed to have the tendency to under-estimate the ductility of the beams.
- The Normalized Mean Square Error (NSM) 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.

Conflict of interest

The authors declare no potential conflict of interest

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Sincerely yours,

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Techno Press

3. First decision: Revised required (11 Mei 2021)

- Reviewers' comments

IV. COMMENTS

1 - Paragraph 2.2 Concrete
Fig.3 be Fig.4, and also need to correct in Fig.

2- Table 5 Ratios must correct

3-Fig.4 be Fig. 5

4- Some references must mention in the References
Siddique and Rouf (2006)
ASTM C 1018–97 (1998)
Ashour (2000)
Yang et al. (2018).
Nielsen and Cao 2010,
Godat et al. 2010
Hanoon et al. 2016)
Metwally 2012

5- An increment in the w/c ratio from 0.30 to 0.35 was discovered to have reduced the compressive strength by 54% as observed from 21.88 to 18.48 MPa

54% need to check and correct.

IV. COMMENTS

1. Remove Grammatical and spelling errors
2. Increase Number of beams at least three beams for each W/C ratio for comparison of results.
3. Slump values of each w/c ratio and superplasticizer
4. If possible then add basic properties of Polypropylene waste coarse aggregate (PWCA).
5. In figure 6, there should be three point bending test, but not be three point pending test

4. Manuscript resubmission (21 Mei 2021)

- Response to reviewers
- Revised version with highlight

Manuscript AMR12104XC
Response to Reviewers

Dear Editor-in-chief Advances in Materials Research, *An International Journal*,

Thank you for giving us the opportunity to submit a revised draft of the manuscript "The flexural behavior of RC beams with sand-coated PWCA at different w/c ratios" for publication in the journal of Advances in Materials Research, *An International Journal*. We appreciate the time and effort that you and the reviewers dedicated to providing feedback on our manuscript and are grateful for the insightful comments on and valuable improvements to our paper. We have incorporated most of the suggestions made by the reviewers. Those changes are highlighted within the manuscript in red colored texts. Please see below for a point-by-point response to the reviewers' comments and concerns. All page and line numbers refer to the revised manuscript file (main document).

Reviewers' Comments to the Authors

A. Reviewer 1

1. **Comment from Reviewer 1:** Remove grammatical and spelling errors.

   Author(s) response: We appreciate the positive feedback from the reviewer. The authors have addressed the reviewer's concern about the grammatical and spelling errors. Moreover, the paper has been checked and corrected by professional native speaker proofreader to improve its readability.

2. **Comment from Reviewer 1:** Increase number of beams at least three beams for each W/C ratio for comparison of results.

   Author(s) response: Thank you for pointing this out. Although we agree that this is an important consideration, the number of the beams cannot be increased in this manuscript due to time and cost constraints. However, we believe this study makes a valuable contribution to the field since it presents useful information for understanding the effect of water/cement (w/c) ratio on the flexural behavior of reinforced concrete (RC) beams which contain polypropylene waste coarse aggregates (PWCA) coated with sands subjected to concentrated monotonic load. As a potential limitation of the study, we have suggested that the number of the beams need to be increased in the the future work. The sentences read as follows in point 9 of the conclusion on Page 13 Line 37–38:

   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.

3. **Comment from Reviewer 1**: Slump values of each w/c ratio and superplasticizer.

   Author(s) response: Thank you for the reviewer's concern. We have modified Table 5 in Page 6 to address the comment raised by the reviewer. The revised table is as follow:

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*

4. **Comment from Reviewer 1**: If possible then add basic properties of Polypropylene waste coarse aggregate (PWCA).

   Author(s) response: We agree with the reviewer's assessment. Accordingly, throughout the manuscript, we have added the the physical properties of S-PWCA to address the comment raised by the reviewer. The revised text can be found on Page 4 Line 20–21 and in Table 3. Thank you for the reviewer's concern.

   The final sand-coated polypropylene waste coarse aggregates (S-PWCA) are presented in Fig. 3 while their physical properties are listed in Table 3.

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*

5. **Comment from Reviewer 1**: In figure 6, there should be three point bending test, but not be three point pending test.

   Author(s) response: Thank you for pointing this out. We have modified the caption of Figure 6 on Page 7 to address the comment raised by the reviewer as follow:

Fig. 6 Three-point bending test for RC beam

B. Reviewer 2

1. **Comment from Reviewer 2:** Paragraph 2.2 Concrete Fig. 3 be Fig. 4, and also need to correct in Fig 5.

   Author(s) response: We appreciate the positive feedback from the reviewer. The authors have addressed the reviewer's concern about the order of the figures in the revised manuscript. Thank you.

2. **Comment from Reviewer 2:** Table 5 Ratios must correct.

   Author(s) response: We agree with the reviewer's assessment. Accordingly, throughout the manuscript, we have modified Table 5 (revised to Table 6) on Page 7 to address the comment raised by the reviewer. Thank you for the reviewer's concern.

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

3. **Comment from Reviewer 2:** Fig. 4 be Fig. 5.

   Author(s) response: We appreciate the reviewer for helping us in improving this manuscript. We would like to answer the reviewer's comment similar with the above point 1. Thank you for the reviewer's concern.

4. **Comment from Reviewer 2:** Some references must mention in the References: Siddique and Rouf (2006), ASTM C 1018–97 (1998), Ashour (2000), Yang et al. (2018), Nielsen and Cao 2010, Godat et al. 2010, Hanoon et al. 2016, Metwally 2012.

   Author(s) response: Thank you for the reviewer's concern and we agree with the reviewer's assessment. Accordingly, throughout the manuscript, we have provided the above mentioned references. The revised text can be found in the references section with red colored text as follow:

Ashour, S.A. (2000), "Effect of compressive strength and tensile reinforcement ratio on flexural behavior of high-strength concrete beams", Eng. Struct., ***22****(5), 413–423. https://doi.org/10.1016/S0141-0296(98)00135-7.*

ASTM C1018-97 (1998), Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading), American Society for Testing and Materials: West Conshohocken, Pennsylvania, USA.

Godat, A., Qu, Z., Lu, X., Labossiere, P., Ye, L.P. and Naele, K.W. (2010), "Size effects for reinforced concrete beams strengthened in shear with CFRP strips", J. Compos. Constr., 14(3), 260–271. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000072.

Hanoon, A.N., Jaafar, M.S., Hejazi, F. and Aziz, F.N.A.A. (2016), "Energy absorption evaluation of reinforced concrete beams under various loading rates based on particle swarm optimization technique", Eng. Optim., ***49****(9), 1483–1501. http://dx.doi.org/10.1080/0305215X.2016.1256729.*

Metwally, I.M. (2012), "Evaluate the capability and accuracy of Response-2000 program in prediction of the shear capacities of reinforced and prestressed concrete members", HBRC J., ***8****, 99–106. https://doi.org/10.1016/j.hbrcj.2012.09.005.*

Nielsen, M.P. and Cao. H.L. (2010), Limit Analysis and Concrete Plasticity, CRC Press, NewYork, NY, USA.

Siddique, M.A. and Rouf, M.A. (2006), "Effect of material properties on ductility of reinforced concrete beams", J. Inst. Eng. Malay., ***7****(3), 33–37.*

Yang, K.H., Mun, J.S. and Lee, H. (2014), "Workability and mechanical properties of heavyweight magnetite concrete", ACI Mater. J., ***111****, 273–282. https://doi.org/10.14359/51686570.*

5. **Comment from Reviewer 2:** An increment in the w/c ratio from 0.30 to 0.35 was discovered to have reduced the compressive strength by 54% as observed from 21.88 to 18.48 MPa.

   54% need to check and correct.

   Author(s) response: Thank you for pointing this out. We have modified the sentence to address the comment raised by the reviewer. The revised text reads as follow on Page 13 Line 16–19:

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

Gandjar Pamudji*[1], Yanuar Haryanto[1,2a], Hsuan-Teh Hu[2,3], Farida Asriani[4], Laurencius Nugroho[2]

[1]Department of Civil Engineering, Faculty of Engineering, Jenderal Soedirman University, Jln. Mayjen. Sungkono KM 5, Blater, Purbalingga, 53371, Indonesia
[2]Department of Civil Engineering, College of Engineering, National Cheng Kung University, No. 1 University Road, Tainan, 701, Taiwan (R.O.C.)
[3]Department of Civil and Disaster Prevention Engineering, College of Engineering and Science, National United University, No. 2, Lien Da, Nan Shih Li, Miaoli, 36063, Taiwan (R.O.C.)
[4]Department of Electrical Engineering, Faculty of Engineering, Jenderal Soedirman University, Jln. Mayjen. Sungkono KM 5, Blater, Purbalingga, 53371, Indonesia

(Received keep as blank , Revised keep as blank , Accepted keep as blank)

Abstract. The aim of this study was to investigate the effect of water/cement (w/c) ratio on the flexural behavior of reinforced concrete (RC) beams which contain polypropylene waste coarse aggregates (PWCA) coated with sands subjected to concentrated monotonic load. The process involved the experimental manufacturing of three RC beams with sand-coated PWCA concrete using 0.30, 0.35, and 0.36 w/c ratios at a width of 80 mm, a height of 160 mm, and a length of 1600 mm. The flexural performance, including load-deflection relationship, flexural strength, ductility index, stiffness, as well as toughness was investigated and discussed. Moreover, the analytical approach was verified using the Response-2000 program by comparing the analytical and experimental results. The sand-coated PWCA RC beams were discovered to have the ability to sustain the loads applied effectively by producing a flexural performance which is considered acceptable and reasonable. In addition, the variations in the w/c ratio were observed to have effects on the parameters of the beams investigated. Finally, the ultimate loads recorded for these beams confirmed their acceptability in the analytical investigation.

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

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,

∗Corresponding author, Assistant Professor, E-mail: gandjar.pamudji@unsoed.ac.id
[a] Associate Professor, E-mail: yanuar.haryanto@unsoed.ac.id

section, 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, impervious 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 Lofti-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.

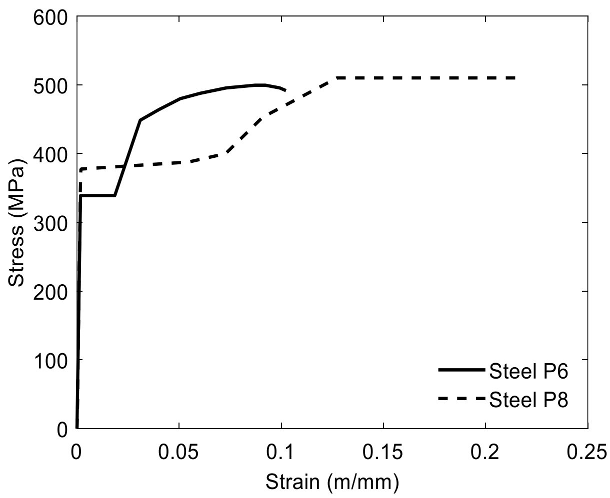


Fig. 1 Tensile stress-strain curves of reinforcement steel

Table 1 Reinforcement steel bars

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

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.

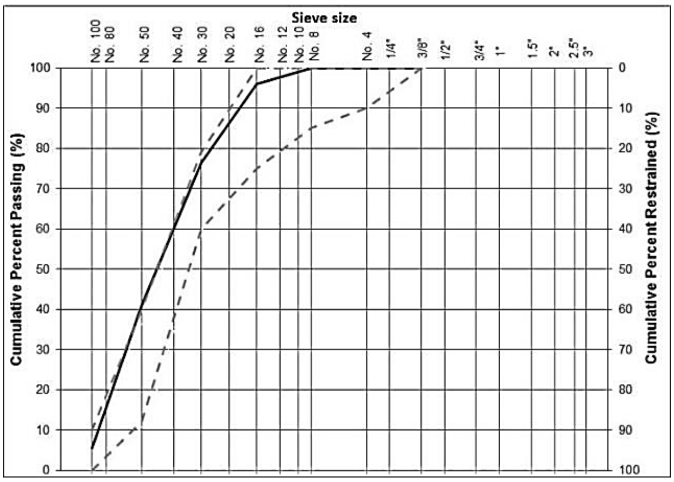


Fig. 2 Grading size distribution of sand (Pamudji *et al.* 2020)

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

Properties	Test results
Dry loose density (g/cm3)	1.62
Specific gravity (SSD)	2.63
Absorption (%)	1.47
Fineness modulus	1.81

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 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.

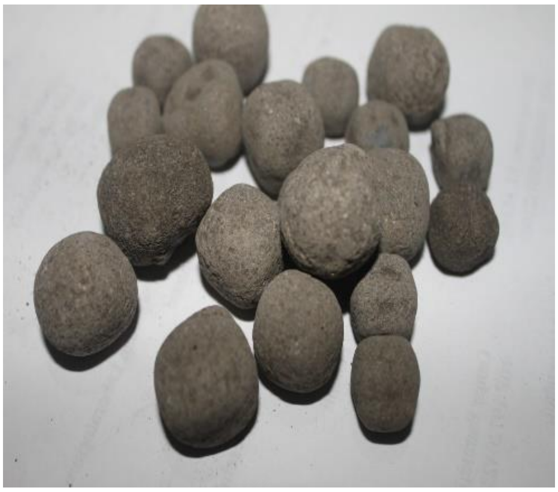


Fig. 3 Polypropylene waste coarse aggregate coated with sand

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

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.

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

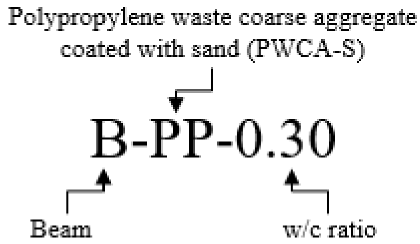


Fig. 4 The designation symbols for the concrete mix

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 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, Appa Rao 2001, Fernandes *et al.* 2005), heavyweight concrete (Yang *et al*. 2014, Lofti-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.* 2015). Moreover, all the concretes are applicable for structural purposes since they all satisfied the 17 MPa minimum compressive strength required by ACI code ACI 318M-14 (2014).

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

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

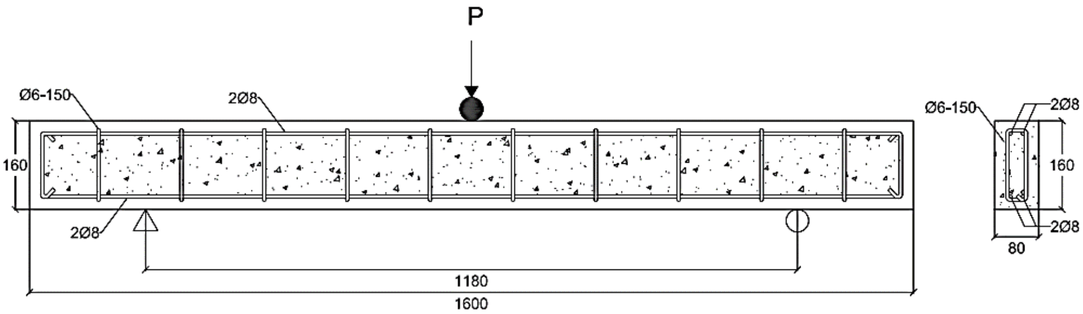


Fig. 5 The dimensions and reinforcement of RC beams

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.


Fig. 6 Three-point bending test for RC beam

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.

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.

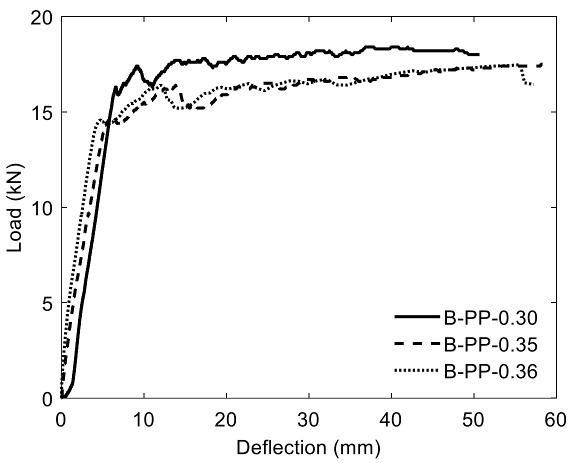


Fig. 7 Load-deflection curves for all specimens

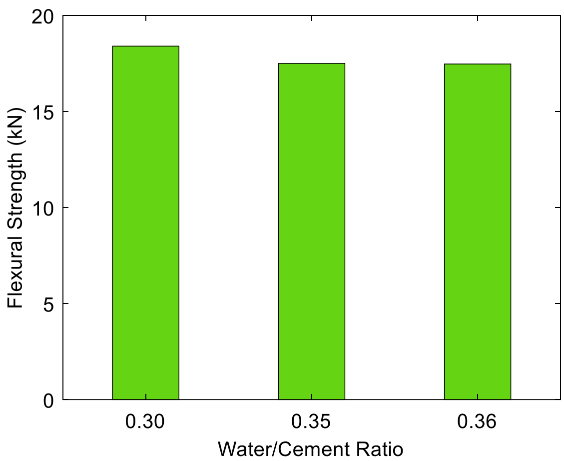
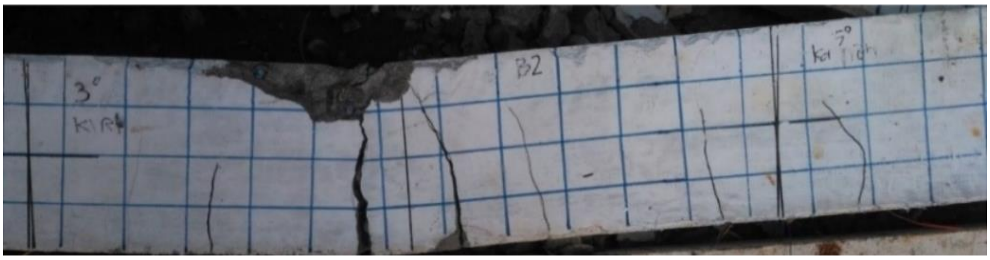


Fig. 8 Flexural strength vs w/c ratio

(a) B-PP-0.30

(b) B-PP-0.35



(c) B-PP-0.36

Fig. 9 Failure modes for the beams

3.2 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 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.

$$\mu\Delta = {}^{\Delta_u}\!/_{\Delta_y} \quad (1)$$

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.

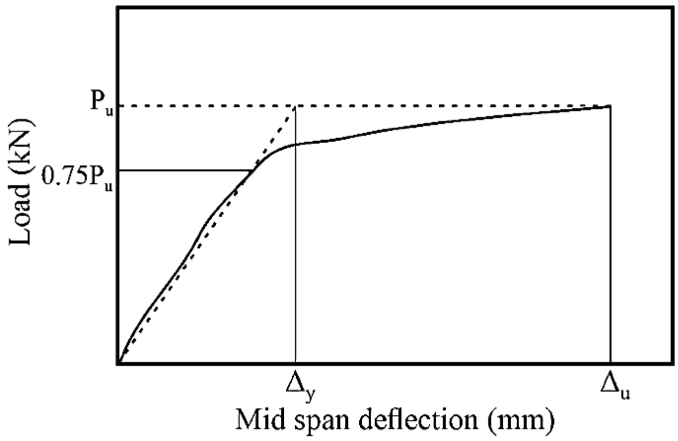


Fig. 10 Typical load-mid span deflection for RC beams

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.

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

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 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.

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

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.

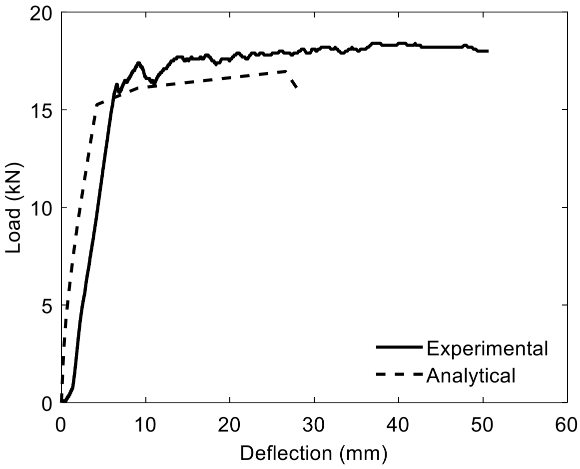
Table 9 Toughness value for the beams

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

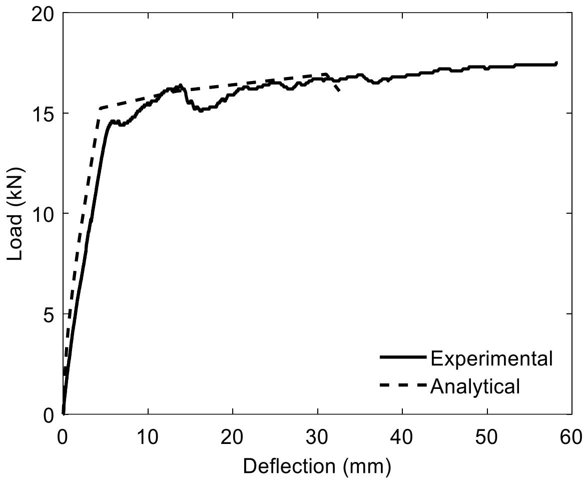
4. Analytical investigation

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 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).

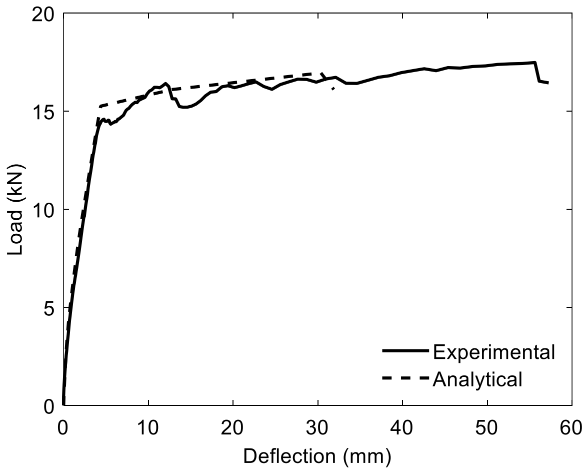
The three beams tested were modeled and analyzed to ensure the analytical model's validation and accuracy after which the data predicted by the R2K program and those obtained from the experiment were compared. The experimental and predicted values for the load versus mid-span deflection at all stages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



(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

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 (NSM) 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 (NSM) 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.

Conflict of interest

The authors declare no potential conflict of interest.

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

Gandjar Pamudji*[1], Yanuar Haryanto[1,2a], Hsuan-Teh Hu[2,3], Farida Asriani[4] and Laurencius Nugroho[2]

[1] *Department of Civil Engineering, Faculty of Engineering, Jenderal Soedirman University, Jln. Mayjen. Sungkono KM 5, Blater, Purbalingga, 53371, Indonesia*
[2] *Department of Civil Engineering, College of Engineering, National Cheng Kung University, No. 1 University Road, Tainan, 701, Taiwan (R.O.C.)*
[3] *Department of Civil and Disaster Prevention Engineering, College of Engineering and Science, National United University, No. 2, Lien Da, Nan Shih Li, Miaoli, 36063, Taiwan (R.O.C.)*
[4] *Department of Electrical Engineering, Faculty of Engineering, Jenderal Soedirman University, Jln. Mayjen. Sungkono KM 5, Blater, Purbalingga, 53371, Indonesia*

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Abstract. The aim of this study was to investigate the effect of water/cement (w/c) ratio on the flexural behavior of reinforced concrete (RC) beams which contain polypropylene waste coarse aggregates (PWCA) coated with sands subjected to concentrated monotonic load. The process involved the experimental manufacturing of three RC beams with sand-coated PWCA concrete using 0.30, 0.35, and 0.36 w/c ratios at a width of 80 mm, a height of 160 mm, and a length of 1600 mm. The flexural performance, including load-deflection relationship, flexural strength, ductility index, stiffness, as well as toughness was investigated and discussed. Moreover, the analytical approach was verified using the Response-2000 program by comparing the analytical and experimental results. The sand-coated PWCA RC beams were discovered to have the ability to sustain the loads applied effectively by producing a flexural performance which is considered acceptable and reasonable. In addition, the variations in the w/c ratio were observed to have effects on the parameters of the beams investigated. Finally, the ultimate loads recorded for these beams confirmed their acceptability in the analytical investigation.

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,

*Corresponding author, Assistant Professor, E-mail: gandjar.pamudji@unsoed.ac.id
[a] Associate Professor, E-mail: yanuar.haryanto@unsoed.ac.id

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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, impervious 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.

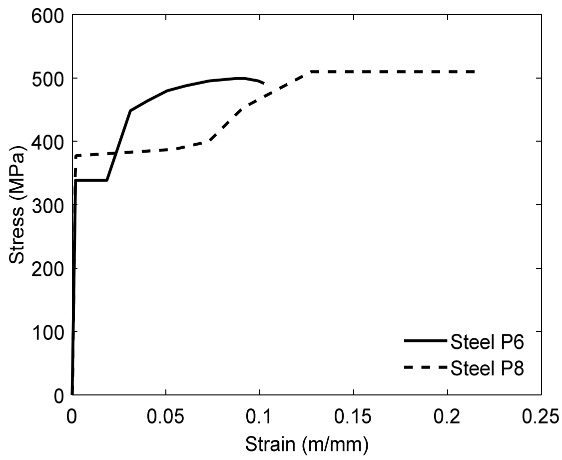


Fig. 1 Tensile stress-strain curves of reinforcement steel

Table 1 Reinforcement steel bars

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

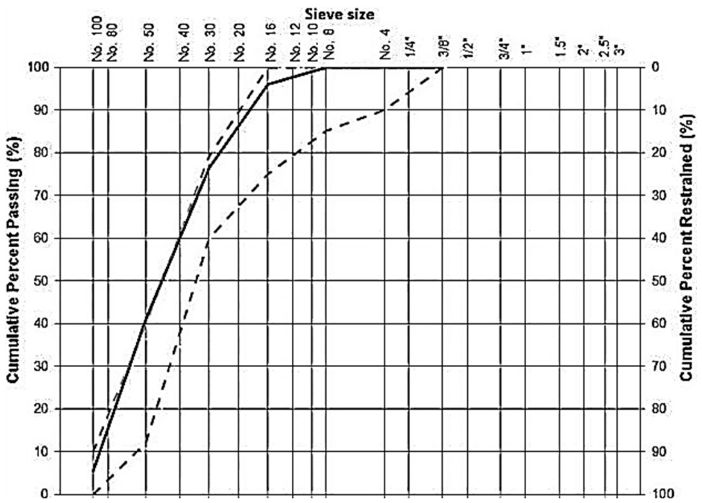


Fig. 2 Grading size distribution of sand (Pamudji *et al*. 2020)

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

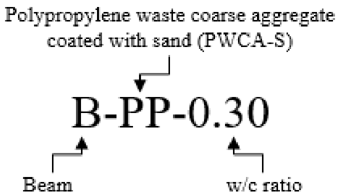


Fig. 4 The designation symbols for the concrete mix

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

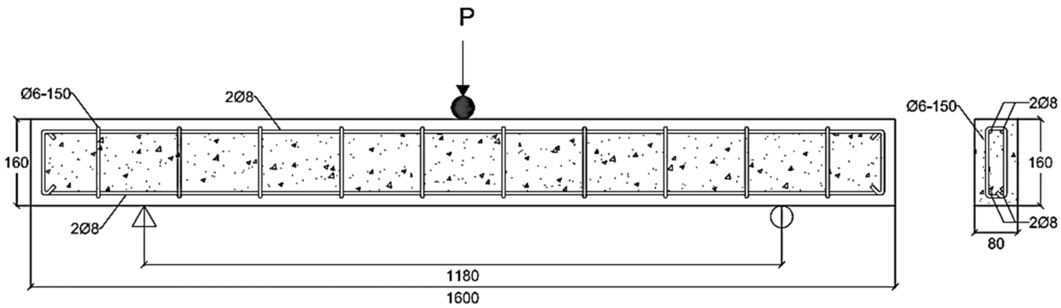


Fig. 5 The dimensions and reinforcement of RC beams


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.

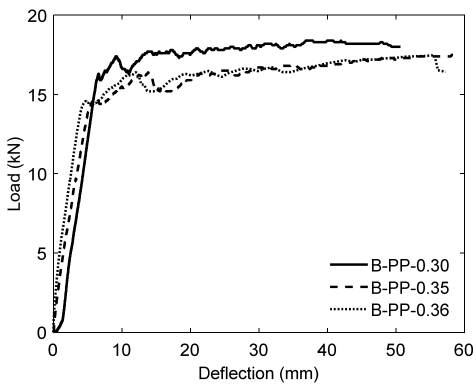


Fig. 7 Load-deflection curves for all specimens

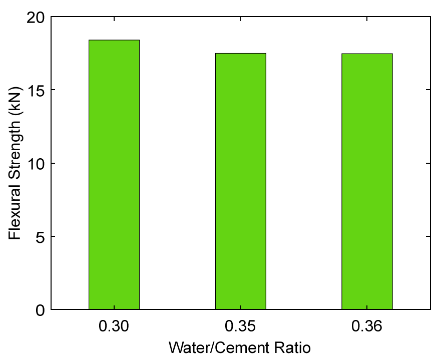
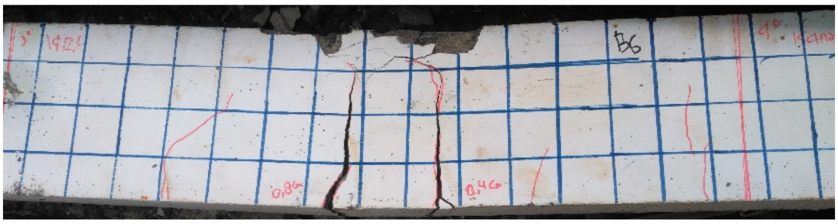
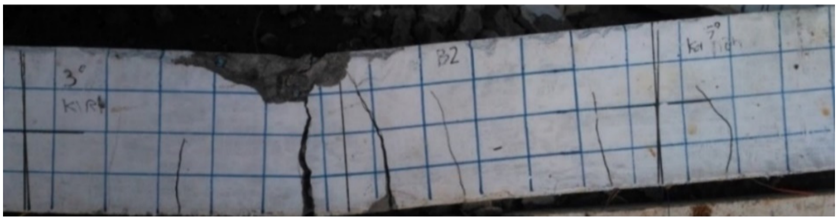


Fig. 8 Flexural strength vs w/c ratio

(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

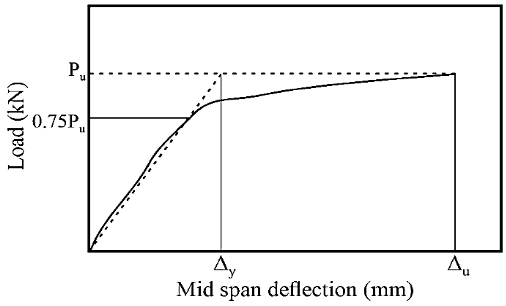


Fig. 10 Typical load-mid span deflection for RC beams

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

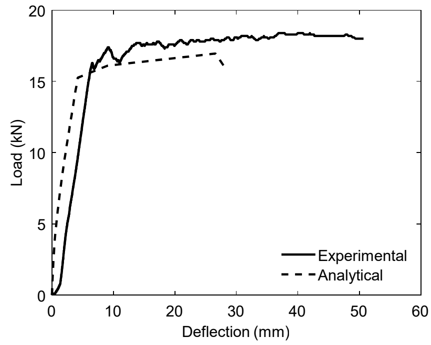
obtained in this study are indicated in Table 8. It was discovered that there was an increase in the stiffness due to the increment in the w/c ratio, thereby causing a reduction in the compressive strength of the concrete. This is, however, observed to be different from previous findings by Ashour (2000) 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

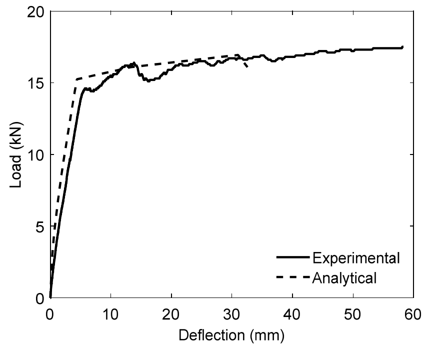
Toughness is defined as a specimen's ability to absorb energy and is also explained to be the quantity of energy needed to break a specimen. It is considered an indicator of structural integrity like strength and ductility due to its ability to sustain the system unity when placed under unusual physical 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

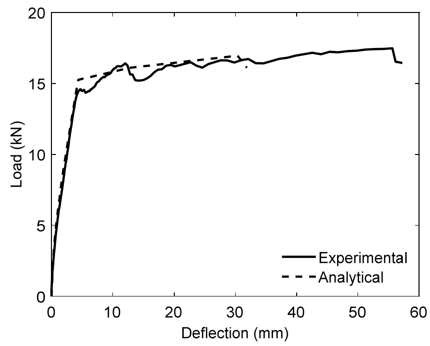
An analytical investigation was conducted using a program designed through the Modified Compression Field Theory (MCFT) which is known as Response-2000 (R2K) (Bentz 2000). This



(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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