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Mix design and tests on structural lightweight concrete contained plastic waste aggregate

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Abstract: In this study, an encouraged attempt was made to produce a structural lightweight concrete (LWC) containing plastic waste aggregate (PWA). Mix design was made based on calculating total surface area of natural aggregate and PWA but there was a need for trial mixes. On replacing 75% of natural fine aggregate for a mix with 45 MPa design strength with PWA, the researchers were able to produce structural LWC. On using PWA in the mixture, density was reduced from 2375 kg/m^3 to 1917 kg/m^3, compressive strength reduced from 47.78 MPa to 17.66 MPa, splitting tensile strength reduced from 3.58 MPa to 1.71 MPa and modulus of elasticity reduced from 27152 MPa to 13854 MPa. Performance of the produced LWC was assessed via testing beams and investigating steel-concrete pull-out strength. The structural behavior of the produced LWC is, in general, similar to the normal concrete but with reduced performance mainly because of the compressive strength reduction.

Keywords: Compressive strength, Concrete beam, Lightweight concrete, Plastic waste aggregate, Pull-out strength

1. Introduction

Plastic is non-biodegradable, and its increased use leads to some adverse effects on the environment by littering roadsides, clogging sewer lines, and filling land (Kumar et al., 2025). A huge amount of post consumed plastic of different sorts are available and there is a need for recycling of such solid waste to avoid further pollution of land and water. Researchers worldwide have attempted to use this material to produce a plastic aggregate contained recycled concrete. The research works were mainly focused on investigation of variation of different properties of concrete because of natural aggregate replacement with plastic waste aggregate (PWA). There is a relatively large amount of test data on this topic of concrete technology and properties of concrete containing different kinds of PWA are now well disclosed. There is no doubt that because of its lightweight nature, using PWA instead of natural aggregate leading to concrete density reduction, but unfortunately, PWA addition to concrete is mostly accompanied with mechanical properties deterioration. For instance, Mohammed et al. (2019) observed a continuous reduction of both compressive strength and density when PVC waste aggregate ratio increased in concrete mix as natural coarse or fine aggregate replacement. On replacing 85% fine aggregate with PVC waste aggregate, there was a compressive strength reduction from 41.51 MPa to 16.4 MPa and density reduction from 2447 kg/m^3 to 2055 kg/m^3. On replacing coarse aggregate with PVC aggregate, the reduction was higher and found to be 8.3 MPa and 1695 kg/m^3. One can note that when 85% natural aggregate is replaced with PVC aggregate the obtained mix could not be categorized as structural lightweight concrete (LWC). ACI 213R-87 (1994) uses density to categorize concrete according to its application and there are three categories. Structural lightweight concrete has a density between 1350 and 1900 kg/m^3, as its name implies, this concrete is used for structural purposes and has a minimum compressive strength of 17 MPa. In general, for concrete mixes, there is a direct relation between compressive strength and unit weight of concrete and there are many test data documents this fact. Lightweight concrete (LWC) mix design is based on balancing between compressive strength and unit weight of concrete. Table 1 shows test data taken from some past experiments on changing density and 28 days compressive strength because of PWA addition to concrete. In these tests, fine aggregate was replaced with

PWA, otherwise it was indicated in the footnote of the table. One can observe that with reducing density compressive strength usually reduces and the compatibility between the two properties not exists to fall within the limits of ACI 213R-87 (1994). Consequently production of PWA LWC needs further efforts. By Khalil and Al Obeidy (2018), one mix falls within the limits of the specification (of density 1862 kg/m^3 and compressive strength of 29.5 MPa) when all coarse aggregate was replaced PWA. Since concrete mixture usually containing natural coarse aggregate, the authors think that this mix could not be used for structural purposes.

Reviewing literature indicates that, as the authors think, there is no serious attempt to make a mix design of PWA concrete to produced structural LWC. In fact, the past researches were focused on investigation of the residual concrete properties because of natural aggregate replacement with PWA. For this purpose, this research has been arranged to fill this gap, and the main objective is the production of structural LWC mixture containing PWA. In the first part of this study, a mix design was performed via preliminary estimation of the aggregate surface area and trial mixes. Later, a test program was arranged to investigate some properties of the designed mixture and flexural behavior of concrete beams in addition to the pull-out strength of steel rebar embedded in concrete, The outcomes of this study is important and paves way for this novel concrete to be a good candidate for the structural applications.

2. Materials

Ordinary Portland cement (CEM I 42.5 R) was used throughout this study. The cement was packed airtight, stored in a dry place in the laboratory, and covered with a plastic sheet after each mixing batch to protect it from moisture and humidity. Crushed stone coarse aggregate was used for concrete mixes with a maximum size of 12.5 mm. For the coarse aggregate, saturated surface dry bulk specific gravity was 2.65, loose bulk density was 1430 kg/m^3, and dry rodded bulk density was 1560 kg/m^3. Natural river sand with a fineness modulus equal to 3.05, saturated surface dry specific gravity equal to 2.66, loose bulk density of 1700 kg/m^3, and dry rodded bulk density of 1850 kg/m^3. Sieve analysis was conducted on the aggregates according to ASTM C136/C136M specification (2019). Fig. 1 shows the grading of fine and coarse aggregates from which one observes that the aggregates conform to the ASTM C33/C33M specification (2021). It should be noted that the material finer than 75 μm was 1% smaller than 3% recommended by ASTM C33/C33M (2021). Potable drinking water was used for mixing concrete and curing specimens.

To produce a PWA pellet, different sorts of post consumed plastics were collected from different disposal areas and brought to the recycling plant. They were well cleaned and washed before they were fed into the melting machine. The machine operated at a constant temperature and pressure for melting the plastics granules. After this process, the pelletized material was collected from the out take of the machine, allowed to cool down and cut to a desired length. The detail of the procedure of making this plastic pellet is given by Faraj et al. (2023). Fig. 2 shows the plastic aggregate obtained from the recycling process. With regard the size, sieve analysis was made and found that the plastic particles passed by 100% on 4.75 mm sieve and passed by 1.82% on 2.36 mm sieve, and accordingly majority of size falls between 4.75 mm and 2.36 mm. Specific gravity was found to be 0.8, loose bulk density was 485 kg/m^3 and compacted bulk density was 537 kg/m^3. One can observe a relatively lightweight nature of the plastic as compared with the natural aggregates used in this study.

3. PWA LWC mix design

Classification of concrete on the basis of density is sensible because density and strength are largely concomitant (Neville, 1995). In this study, to produce PWA LWC, the authors have tried to design a mix with density close to 1900 kg/m^3 and compressive strength not smaller than 17 MPa. It should be noted that the plastic particles' smooth surface texture has an appreciable effect on compressive strength loss.

Design of control mix without plastic aggregate was done for a mix with 45 MPa compressive strength and an average slump of 75 mm using the recommendation of ACI 211 committee (1994). Results showed the following: cement = 514.3 kg/m^3, water = 216 kg/m^3, coarse aggregate = 826.8 kg/m^3 and fine aggregate = 768 kg/m^3. To produce LWC mix contained PWA based on the control mixture, there is a need to replace part of fine aggregate with PWA Pellet. Jafr et al. (2023) used a procedure based on surface area of aggregate to calculate density and compressive strength losses, and this procedure is well considers shape and size of aggregate via calculating total surface area of aggregate particles. In this procedure, fine aggregate particles are divided as sand particle (passing on 4.75 mm and retained on 0.075 mm) and dust particle (passing on 0.075 mm). With regard the shape of particles, sand particle is assumed to be cylindrical while the dust is assumed to be spherical. Results of calculations showed that average particles size of sand of properties given in section 2 is 1.733 mm and that of plastic pellet is 3.53 mm. Average size of dust was approximately taken as 0.04 mm. Now, there is a chance to calculate volume ratio of PWA based on target density and target strength to produce LWC mix.
To calculate the change in concrete density because of PWA addition, the below steps are followed:

Initial unit weight of control mix without PWA (W_i) (in kg/m^3) is given by (Jafr et al., 2023)

$$W_i = W_w + W_c + W_{CA} + W_{FA} \qquad (1)$$

Final weight of fresh concrete containing PWA as fine aggregate replacement (W_f) (in kg/m^3) is given by

$$W_f = W_w + W_c + W_{CA} + W_{FA}\left[\frac{S_{AN}\,(1-V_p) + S_{AP}V_p}{S_{AN}}\right] \qquad (2)$$

Where W_w is weight of water, W_c is weight of cement, W_{CA} is weight of coarse aggregate and W_{FA} is weight of fine aggregate, all in kg/m^3. V_p is volume ratio of fine aggregate replacement with PWA, S_{AN} is total surface area of natural aggregate and S_{AP} is total surface area of PA.

From Eq. 1, $W_w + W_c + W_{CA} = W_i + W_{FA}$ and on substituting in Eq. 2 and simplifying one obtains

$$V_p = \frac{(W_f - W_i)\, S_{AN}}{W_{FA}(S_{AP} - S_{AN})} \quad (3)$$

Having initial weight (normal weight mix) and final weight mix (lightweight mix) one can calculate volume of PA using Eq. 3.

Now, there is a need to calculate PA ratio based on strength change. If R_c is the ratio of final strength to initial strength, the procedure given by Jafr et al. (2023) will lead to the following equation

$$V_p = \frac{(1 - R_c)\, S_{AN}}{(S_{AN} - S_{AP})} \quad (4)$$

Results of calculation indicates that S_{AN} = 9658 m^2/m^3, S_{AP}= 1100 m^2/m^3, V_p = 0.882 based on density consideration (1900 kg/m^3) and V_p = 0.677 based on strength consideration (17 MPa).

For testing compressive strength and density, 100 x 200 mm cylindrical steel mould was used, concrete was cast in two layers and each layer was vibrated on a vibrator table. For each concrete mix, three cylinders were cast and tested and the average results were recorded beside the standard deviation.

4. Results of LWC mix design

Results of section 3 will lead to two mixes, one with PWA volume ratios of 0.882 and 0.667. Indeed, there is a need for control mix (without PWA) to compare the change of density and compressive strength. The authors have attempted to investigate other mixtures via playing with concrete constitutive materials. Properties of trial mixes and results of testing are given in Table 2. The used two values of V_p based on density and compressive strength will not lead to a desired LWC mix, because if one works on PWA ratio of 0.882, the strength will be too low (10.81 MPa) and on working on the PWA ratio of 0.677, density will be 1960 kg/m^3, higher than 1900 kg/m^3. Therefore, justification is required and the solution is in the fine aggregate increase in control mix. Some trials were made and found that if fine aggregate content is increased by 30% to be 1000 kg/m^3, there is a chance to produce a LWC mix with PWA ratio of 0.677. In order not to change the total aggregate content, coarse aggregate must be reduced by 30% to be 594.8 kg/m^3. Because of fine aggregate increase, reduction in compressive strength is expected, and to overcome this, cement was increased by 20% to be 617.2 kg/m^3. It will be noted that on this modification, compressive strength of control mix was reduced from 44.96 MPa to 31.07 MPa (Mix 5), indicating a vital role of fine aggregate on the strength. This modification was not useful since the strength was not changed and density reduced by a small amount to be 1939 kg/m^3 (Mix 4). Another modification was made via increasing cement by 20%, reducing water by 10% and using high range water reducer (HRWR) by 0.5%. This attempt was found good since strength was increased to be 20.60 MPa and density was reduced to be 1939 kg/m^3 (Mix 6). To reduce further the density, another attempt was made to prepare a mixture with V_p equal to 0.75. For this mix, PWA was found to be 225.6 kg/m^3 and fine aggregate became 250 kg/m^3. The results of this mix are somewhat good since the density was reduced to 1917 kg/m^3 and compressive strength was increased to be 17.21 MPa. Control mix for this case is Mix 8, with density equal to 2375 kg/m^3 and compressive strength equal to 47.78 MPa. The designed mixture based on the preliminary estimation of surface area of aggregate and trial mixes is Mix 7, and there is need to study the properties of the designed structural LWC.

5. Tests on designed PWA LWC

It is important to have an idea about the common properties of the designed mix and compare the behavior with that of normal weight concrete (Mix 8). To do this, several important tests were made to assess structural performance of the designed concrete mix. Tests were performed to assess properties of compressive stress-strain relationship (to assess compressive strength and modulus of elasticity in addition to the deformation), splitting tensile strength, flexural strength and deformation of reinforced concrete (RC) beam and pull-out strength and deformation of embedded steel rebar in concrete. Compressive stress-strain relationship and modulus of elasticity was made on 150 x 300 mm cylinder following the recommendation of ASTM C469 Specification (2013) and splitting tensile strength was made on 100 x 200 mm cylinder following ASTM C496 Specification (2013). For each concrete mix, three cylinders were cast and tested and the average results were recorded beside the standard deviation.

For casting beam specimens, a wooden mould shown in Fig. 3 was used with inner surfaces thoroughly oiled before casting. Beam length was 1200 mm and cross section was 150 x 200 mm (width x height) tested on a simple span of 1000 mm under central point load (see Fig. 4). Two #10 mm steel bars of an average yield stress of 637.8 MPa and ultimate tensile stress of 665.3 MPa were used as tension reinforcement. Two beams were cast and tested, one made of NWC and the other made of LWC. After 24 hrs from casting, the mould was released and fully covered with burlap and continuously sprayed with water for 28 days. All specimens were left in the laboratory for 7 days to dry and then tested. Loading rate was kept to be 0.25 kN/sec and applied monotonically till failure. For measuring central deflection, a digital dial gauge was erected at the center of the beam and for measuring strain in steel rebar, a 6 mm strain gage was fixed at the center of one rebar. The detail of measurement units is observed in Fig. 4.

For steel rebar pull-out test, #10 mm rebar was embedded in standard 150 mm cube in a manner shown in Fig. 5, and to ensure smooth concrete contact surface during pulling out a special timber mould was prepared as shown in Fig. 6. After casting, the specimen was taken out from the mould after 24 hrs and put in water tank for curing for 28 days. Fig. 7 shows one specimen ready for testing. Thee specimens made of PWA LWC were prepared and another three specimens made of NWC mix.

6. Results and discussion

6.1 Density

Based on the test data obtained, average dry density of NC is 2375 kg/m^3 with S_D equal to 27.3 kg/m^3 while that of LWC is equal to 1917 kg/m^3 with S_D equal to 54 kg/m^3. According to the obtained results, dry density ratio of LWC is 81% compared with that of NC.

6.2 Compressive strength

Average compressive strength of NC is 47.78 MPa with S_D equal to 1.48 MPa while that of LWC is equal to 17.66 MPa with S_D equal to 0.454 MPa. According to the obtained results, compressive strength ratio of LWC is 37% compared with that of NWC. One can note that the compressive strength is within the limits of structural LWC (higher than 17 MPa).

6.3 Splitting tensile strength

Based on the test data on second series test, average splitting tensile strength of NWC is 3.58 MPa with S_D equal to 0.29 MPa while that of LWC is equal to 1.71 MPa with S_D equal to 0.24 MPa. According to the obtained results, splitting tensile strength ratio of LWC is 48% compared with that of NWC.

6.4 Compressive stress-strain relationship and modulus of elasticity

Fig. 9 shows compressive stress-strain relationship for NC and plastic aggregate LWC. From the results of compressive stress-strain relationship, there is a chance to calculate modulus of elasticity of concrete following the recommendation of ASTM C469 specification (2013) as follows:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050} \tag{5}$$

in which E = chord modulus of elasticity, MPa

S_2 = stress corresponding to 40% of ultimate stress, MPa

S_1 = stress corresponding to longitudinal strain, ε_1, of 50 millionth, MPa, and

ε_2 = longitudinal strain produced by stress S_2.

For NWC average modulus of elasticity is equal to 27152 MPa with S_D equal to 4319 MPa while for LWC average modulus of elasticity is equal to 13854 MPa with S_D equal to 3196 MPa. Accordingly, the ratio of elastic modulus for LWC to that of NWC is 51%.

With regard the strain corresponding to peak stress, for NWC the average value is 0.00222 with S_D equal to 0.000142 while for LWC the average value is equal to 0.00174 with S_D equal to 0.000281. One can find that the strain corresponding to peak stress for NWC is 1.28 times that of LWC. Fig. 10 shows cylinder specimens after testing, from which one can observe that NWC specimen is suffered from high cracking near failure as compared with LWC specimen.

6.5 Flexural behavior of beams

Test results indicate that for normal weight concrete beam, ultimate load capacity was 73.78 kN and that for LWC beam was 68.06 MPa. One can observe an excellent load capacity of LWC beam since the ratio is 92% of that of normal weight concrete beam. Flexural capacity of reinforced concrete beams, designed to fail in tension is mainly governed by the amount of reinforcement provided in tension zone, provided that there is a good bond between reinforcement and concrete causing steel rebar yield. In our study, the mode of failure was steel yielding followed by compression failure of concrete near the center of the beam. The lower strength of the LWC was of minor importance, and consequently failure load of the beam was 92% of that of normal concrete beam. Fig. 11 shows load-central deflection of the two beams from which one can find an almost identical ascending portion indicating the similarity of LWC and NWC beams within the serviceability limit. Also, the deflection at which the beams begin to behave plastically is close to each other which are 2.21 mm and 2.25 mm and the average deflection is close to the beam span divided by 450. In this way the flexural performance of the beam made of the designed PW LWC within the serviceability limit is good and close to that of NWC beam. Further, from Fig. 11 one can find that maximum deflection of the two beams is quite similar (24.04 mm and 25.68 mm).

Fig. 12 shows load-steel strain relationship of the two concrete beams. One can find a normal tension failure of the two beams since strain in steel rebar is well larger than that causing yield of steel. In this way, behavior of the beam made of LWC is quite similar to that of NWC beam indicating the usefulness of the designed PW LWC mix.

It is of interest to measure another two important parameters of the beam, deflection ductility and toughness. Deflection ductility is equal to the maximum deflection divided by that at yield of steel rebar. For NWC beam, load corresponding to yield strain yield is equal to 55.08 kN, and the corresponding deflection is 1.57 mm. Consequently, deflection ductility is equal to 15.31 which is a relatively high ductility because the beam was designed to fail in tension. For LWC beam, the mentioned values were found to be 56.1 kN, 2.25 mm and 11.41, indicating a consistency between the two ductilities. One can find that the yield loads f the two beams are close to each other.

With regard the toughness, which is the area under load deflection curve, calculation of toughness indicates 1665.6 kN.mm and 1587.9 kN.mm for NWC beam and LWC beam respectively, indicating the similarity of the two beams, since the ratio of LWC beam to that of NWC beam is 95%. Totally, the designed beam based on PW LWC behaves like NWC beam if one considers the strength and deformation.

Fig. 13 shows the two beams after testing. Well distributed flexural cracks left and right of the beam's center line are observed indicating flexural mode of failure. One can find that the NWC beam suffers from more severe cracking damage, mainly because of the fact that LWC contained plastic particles and plastics have the ability to absorb energy and delaying cracking extension.

It is of interest to calculate ultimate load capacity and compare with the test one and for this purpose moment capacity of the rectangular section was calculated following the recommendation of ACI 318 code (2025). Effective depth of the beam was kept to be 175 mm. For NWC beam, depth of compression zone, moment capacity and ultimate load capacity were found to be 15.4 mm, 16752 kN.mm and 67.01 kN, respectively, while for LWC beam, depth of compression zone, moment capacity and ultimate load capacity were found to be 41.7 mm, 15436.1 kN.mm and 61.74 kN, respectively. Consequently, ratio of test/calculated moment and ultimate load for both beams is 1.1 indicating the compatibility between the two beams. In this way, the designed LWC beam contained PWA could be considered as a type of LWC beam and has a potential for structural applications of concrete members subjected to bending. Indeed, further studies on this novel type of beams are required for best usage and applications.

6.6 Steel-concrete pull-out bond

Results of steel-concrete pullout bond are given in Table 3. Bond stress was calculated from dividing pull-out force by the bond area (bar perimeter times embedded depth which is equal to 4712 mm^2). Pull-out strength is equal to 10.08 MPa for NWC and equal to 8.3 MPa for LWC, and accordingly there is a reduction by 17.7% because of using PWA in the mix. However, the pull-out strength of LWC is high and expected to perform good bond action in reinforced concrete members of embedded steel bar subjected to tension. As one observed from sec. 6.5, there was a yield of steel rebar of the tested beam made of LWC (see Fig. 12) and the load-steel strain of the beam is close to that of NWC beam, this indicates a good bond performance of the designed LWC mixture. Fig. 14 shows pull-out force-slip relationship of the two concrete mixtures, from which one can observe that the two relationships are similar to each other but the pull-out strength of LWC tends to be lower mainly because of lower compressive strength as stated before. Fig. 15 shows two pull-out bond specimens after testing. Mode of pull-out failure is concrete splitting. Smaller cracks number and extension are observed for LWC specimens and this behavior is expected since plastic material has the ability to absorb energy. Consequently, the produced concrete containing PWA behaves to be ductile. Serious modification on the compressive stress-strain relationship was observed by Mohammed et al. (2019) when they used PWC aggregate by different ratios in concrete and the ductile behavior in compression can put the fingerprint on the pull-out bond deformation.

7. Limitations of the study

From the foregoing presentation and discussion, one can find that there is a good chance to produce structural lightweight concrete containing plastic waste aggregate. The plastic aggregate used in this study was prepared from recycling plastic wastes to produce relatively regular shaped pellets. The mix design procedure and recommended mix proportions may be suitable for other types of plastic aggregates such as shredded PET or PVC but there is a need for experimental test to check the applicability.

Further, the flexural strength and behavior of the designed plastic aggregate LWC mix was made on one type of concrete beams with regard the section dimensions and reinforcement detail, given in Fig. 4a. It is worthy to perform other investigations on flexural strength and behavior of plastic aggregate LWC via testing other beams of wide range of length, section dimensions, and reinforcement ratio.

The plastic aggregate pellet used in this study had smooth surface which is the main source of compressive strength loss beside the low elastic modulus of the plastic material. Treatment of the plastic surface was made by several investigators to show the effect of this procedure on some properties of concrete including compressive. For example, by Bágeľ and Matiašovský (2010), smooth polymer surface of electric and electronic equipments crushed plastics waste was treated with a combination of different solutions and additives. The procedures followed were found effective to improve the cement paste-plastic grains interfacial bond. There was compressive strength enhancement on the application of water glass solution alone, or with slag or sand in addition to covering the plastic surface with cement slurry. In another study, Abu-Saleem et al. (2021) worked on microwave radiation pre-treatment of PET, high-density polyethylene, and polypropylene to enhance the bond strength between the plastic aggregate and concrete matrix. Based on

their test data, the interfacial transition zone was improved due to PET plastic surface treatment, leading to the concrete strength improvement.
Totally, there is a chance to enhance interfacial bond between plastic surface and cement matrix via some treatments leading to compressive strength enhancement. These procedures facilitate mix design of structural LWC containing plastic aggregate, since the process is accompanied with compressive strength enhancement.

8. Conclusion

Based on the experimental study given in this study and discussion of the results, the following conclusions are drawn:

1- From a modification on 45 MPa grade concrete, the researchers were successfully produced PWA LWC of acceptable properties to be a good candidate beside the other types of LWC for structural applications. The density of the designed mixture is 1917 kg/m^3 and compressive strength is 17.66 MPa contained 75% PWA as fine aggregate replacement.

2- Because of PWA addition to the virgin concrete, there is a reduction in density by 19.3%, reduction in compressive strength by 63%, reduction in splitting tensile strength by 52.2%, and reduction in modulus of elasticity by 49%. Steel-concrete pull-out behavior flexural behavior of beams made of the produced LWC were similar to that of NWC but with some reduced performance mainly because of compressive strength loss because of PWA content in the mixture.

3- There is a need to check the suitability of the mix design procedure and recommended mixes for concrete containing other types of plastic aggregate, different in shape and size from that used in this study.

AI disclosure statement

The authors declare that they have not used any type of generative artificial intelligence for the writing of this manuscript, nor for the creation of images, graphics, tables, or their corresponding captions.

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