Compressive Strength-Ultrasonic Pulse Velocity Relationship of Concrete Containing Plastic Waste

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Abstract. In this paper the relationship between compressive strength and non-destructive behavior of ultrasonic pulse velocity (UPV) of concrete containing different plastic wastes has been investigated. For this purpose, a total of 102 data observations were collected from nine past works on properties of concrete with plastic waste and analyzed. Relationship between both compressive strength and UPV with plastic waste aggregate was found weak. Also, relationship between compressive and UPV is not strong, and in contrast, there is a relatively strong correlation between compressive strength ratio (concrete with plastic waste/control concrete) and UPV ratio. Using regression analysis, an equation was developed for calculating compressive strength of concrete with plastic waste depending on the UPV test data. The proposed equation is helpful to assess the residual compressive strength and consequently the structural health monitoring of those structures made of concrete with aggregate partially replaced with plastic wastes, which depends essentially on test data of UPV and compressive strength of control concrete.

Keywords: Compressive strength, Plastic waste, Recycled concrete, Regression analysis, Ultrasonic pulse velocity

1. Introduction

Different kinds of plastics are nowadays in use and they have become an inseparable and integral part of our life. Post consuming plastics can contribute to an ever increasing volume in the solid waste stream. Among the important ones there are Polyethylene terephthalate (PET), High density polyethylene (HDPE), Unplasticized Polyvinyl chloride (UPVC), Plasticized polyvinyl chloride (PPVC), Low density polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS) and Expanded polystyrene (EPS) (Pacheco-Torgal, 2019, Siddique, 2008). A large volume of plastics consumed by the citizens worldwide usually accompanied with a large amount of wastes. These wastes need to be managed correctly in order to avoid land and water pollutions. Such waste has been thrown in the form of landfilling or been subjected to an incineration (Siddique, 2008, Sadat-Shojai and Bakhshandeh, 2011). Unfortunately, these methods are classified as the non-desired solution in the developed countries, mainly because the plastic is not biodegradable and on burning poisonous gases will release to the air. One can say that on recycling plastic wastes, additional expenses are required for
reprocessing, accompanied with the color change and been extensively investigated by the past researchers and a relatively large amount of test data is now available in the published literature (Gu and Ozbakkaloglu, 2016, Siddique et al., 2008). Among the most important properties of concrete essentially modified with the existence of plastic waste one can mention the compressive strength. Strength and durability of different concrete structures are mostly dependent on this concrete property. Compressive strength gives an overall picture of quality of concrete, because this property is directly related to the structure of the hydrated cement paste. Also, compressive strength of concrete is almost invariably a vital element of structural design (Neville, 2004). Ultrasonic pulse velocity (UPV) test is a long established non-destructive method which determines the velocity of longitudinal waves. The determination consists of measurement of a time taken by a pulse to travel a measured distance (Neville, 2004). The test method is prescribed by ASTM C597-16 and by BS 1881: Part 203: 1986. The velocity of the ultrasonic pulse through concrete is the outcome of the time taken by the pulse to travel through the hardened cement paste and through the aggregate. Neville (2004) reported that there is no physical relation between the compressive strength and UPV. He noted that within limitations the UPV test can be used to assess the strength of concrete. There are many factors governing UPV including richness of the mix with cement, w/c ratio, aggregate content, moisture condition and the existence of steel reinforcement. With regard concrete containing plastic waste which it the issue of the current study, there is another parameter affecting UPV resistance of concrete which is the existence of plastic instead of natural aggregate. Ultrasonic pulse velocity travels inside concrete mass may vary with the existence of plastic because of the fact that UPV resistance of plastic is different from that of normal concrete materials beside the relevant cracks and flaws between plastic particles surface and the hardened cement. Akcaozoglu et al. (2013) reported that UPV value increased when the density of concrete was light, causing a reduction in the transmission of ultrasonic speed. Also, the addition of plastic materials to concrete mix accounts for the porosity and running dispersal of the transmitted ultrasonic speed (Rahmani, 2013). The previous studies show that plastic contained concrete has lower UPV due to development of pores. Rahmani et al. (2013) observed the reduction in UPV with an addition and increase of PET particle content in concrete. SEM analysis shows that the addition of PET particles makes concrete porous (Senhadji et al, 2015). Therefore, lower ultrasonic pulse velocity was recorded for concrete containing PET contents. Ultrasonic pulse velocity of concrete with PVC aggregate was also studied by Senhadji et al. (2015). The ultrasonic wave velocity values of concrete were found to decrease as the amount of PVC granules in the mixture increase. This reduction was attributed to the fact that the elastic properties of concrete and plastic are different, in addition to increasing porosity of concrete and cavities formed by the PVC particles. These factors are able to attenuate the ultrasonic wave by acoustic impedance. Based on their results there is a linear relationship between compressive strength and ultrasonic wave velocity of concrete. This will lead to the fact that the ultrasonic wave velocities can potentially be used to predict the compressive strength of concrete containing PVC aggregate. The following relationship was obtained for the relation between UPV and compressive strength of concrete at the ages of 28 and 90 days.

\[ UPV = 76.08 f_c' + 1807 \]  

In which UPV is the ultrasonic pulse velocity measured in m/s and \( f_c' \) is compressive strength measured in MPa. For the above relationship \( R^2 \) is equal to 0.9337. Properties of concrete containing plastic waste aggregate (PWA) subjected to high temperature were studied by Lima (2012). This researcher found that the incorporation of PWA can cause a degradation of UPV, which found to depend on the replacement ratio of the natural aggregate with PWA. This is explained by the higher porosity of concrete due to the decomposition of PWA. The relationship between residual UPV and compressive strength was found to be nearly linear (see Fig. 1), which confirms the suitability of measuring the UPV as an expeditious and non-destructive test to measure the residual compressive strength of concrete containing PWA exposed to fire.
Based on test data of compressive strength and UPV of normal concrete with PVC aggregate, the following two relationships were obtained by Mohammed et al. (2019).

For fine aggregate replaced with PVC aggregate

\[ UPV = 1521 (f'_c)^{0.3014} \]  \hspace{1cm} (2)

For coarse aggregate replaced with PVC aggregate

\[ UPV = 59.43 f'_c + 2280.9 \]  \hspace{1cm} (3)

\( R^2 \) is equal to 0.83 and 0.908 for the relationships (2) and (3), respectively, applied for aggregate replacement with PVC ratio between 5% and 85%.

The author thinks that there is a relatively large amount of test data on compressive strength and ultrasonic pulse velocity of concrete with different plastic wastes. However, a general relationship for the compressive and UPV is not available to be applied on concrete with different plastic wastes for the purpose of structural health monitoring of those structures made of concrete with plastic waste aggregate. The available proposed relations is applied for one type of concrete and mainly proposed based on a few number of test data. In the current study, a relatively large number of test data has been collected and analyzed for the purpose of developing a more general equation for the relation between compressive strength and UPV.

2. Available Test Data Inspection

In this study, test data obtained by past nine published works (Akcaozog˘lu et al., 2013, Albano et al., 2009, Rahmani et al., 2013, Senhadji et al., 2015, Mohammed et al., 2019, Safi et al., 2013, Correia et al., 2014, Latroch et al., 2018, Al-Hadithi and Al-Ani, 2018) on the properties of concrete with different plastic wastes have been utilized. Test variables attempted by the researchers are given in Table 1. Plastic wastes used by the researchers were found to be PET, PVC from scrapped pipes or sheets, and expanded PVC. Plastic ratios used were varied from 2.5 to a maximum of 85%, used mostly as fine aggregate replacement. As given in Table 1, totally, 102 data points were taken for the regression analysis.
3. Proposed Equation

It is required here to show variations of compressive strength ($f'_c$) and UPV with plastic waste content in addition to the relation between $f'_c$ and UPV, from which the quality of the relation can be assessed. Fig. 2 shows variation of compressive strength with the plastic waste aggregate ratio. In general, there is a compressive strength loss, being increased with increasing plastic waste content, and the trend seems to be nonlinear. There is a relatively weak correlation between $f'_c$ and the plastic waste ratio because the low coefficient of determination ($R^2$) which is only 0.3. Fig. 3 shows variation of UPV with the plastic waste ratio. There is a continuous loss in the UPV when the aggregate is replaced with plastic waste, and there is no chance for this property to be increased. Again, there is a relatively weak correlation between UPV and the plastic waste ratio because the highest $R^2$ was found to be 0.5. The reason of this low correlation of the two properties of concrete with PW ratio is attributed to the fact that different concrete mixes were used by the researchers. So, there is a vital need to construct a correlation based of the compressive strength ratio (concrete with plastic waste/control concrete) and UPV ratio. Fig. 4 shows variation of $f'_c$ ratio with plastic waste ratio and Fig. 5 shows variation of UPV ratio with plastic waste ratio. Highest $R^2$ for the two relationships are 0.67 and 0.75 respectively. Because of lower $R^2$ value, there is a high discrepancy of test data related to the compressive strength variation. This may be attributed to the sensitivity of concrete under compression and changing failure mode attributed to the change of internal structure of the hardened mass, accompanied with the normal aggregate replacement with plastic waste. This effect is well observed at low plastic waste contents as shown in Fig. 4. However, existence of plastic waste aggregate in concrete has a regular effect on UPV value, as observed from Fig. 5. Accordingly, there is chance to calculate UPV ratio of concrete for any plastic waste value.

| Reference                  | Compressive strength (MPa) | Mix proportion, kg/m$^3$ (Control mix) (C:FA:CA) (W/C ratio) | Type of plastic                           | Plastic ratio (% volume) | Number of test data | Remark                                      |
|---------------------------|---------------------------|---------------------------------------------------------------|-------------------------------------------|--------------------------|---------------------|---------------------------------------------|
| Akcaozoglu et al. (2013)  | 43.2, 55.9                | 500:877.575 (250/500)                                        | PET aggregate (MS=4 mm)                  | 30,40,50, 60             | 10                  | -                                           |
| Albano et al. (2009)      | 27.9, 28.9, 21.3, 23      | 24.1:64.9:41.2 kg (0.5)                                       | PET aggregate (Average size =0.26 cm, 1.14 cm) | 10,20                    | 28                  | -                                           |
| Rahmani et al. (2013)     | 35.36, 38.71              | 488.1:654.9:976.1 (0.42)                                      | PET aggregate (MS=7 mm)                  | 5,10,15                  | 8                   | There is an increase in $f'_c$ at 5% and 10% aggregate replacement |
| Senhadji et al. (2015)    | 32.84, 34.1               | 400:470:1320 (0.48)                                          | Scrapped PVC pipe, Graded 0–3 mm and 3–8mm | 30,50,70                 | 8                   | -                                           |
| Mohammed et al. (2019)    | 41.51                     | 455.4:569.3:1138.5 (W/B = 0.38)                               | PVC aggregate (Shredded sheet MS=10 mm)  | 5,15,30,4, 5, 65,85      | 13                  | There is an increase in $f'_c$ at 5% CA replacement |
| Safi et al. (2013)        | 61.9                      | 664.1:1372.4 (Mortar)                                         | Rejected plastic bags (MS=5 mm)          | 10,20,30, 50             | 15                  | -                                           |
| Correia et al. (2014)     | 44                        | 350:800:7:1003.2 (189/350)                                    | Three types of PET waste: coarse (size between 2 and 7.5,15 | 6                       | -                   | -                                           |
11.2 mm), fine (size between 1 and 4 mm) and nearly-spherical pellets obtained from a post heat treatment.

| Latroch et al. (2018) | 40, 42 | 450:1350 g (Mortar) (W/C = 0.5) | Expanded PVC aggregate | 15, 25, 50, 75 | 10 | - |
|-----------------------|--------|---------------------------------|------------------------|----------------|----|---|
| Al-Hadithi and Al-Ani (2018) | 69 | 450:900:750 (W/B = 150/500) | PET aggregate (MS=4.75 mm) | 2.5, 5, 7.5 | 4 | - |

* MS = Maximum size of aggregate, \( f'_{c} \) = Compressive strength, C=Cement, B=Binder, W=Water, CA= Coarse aggregate, FA= Fine aggregate.

**Figure 2.** Variation of \( f'_{c} \)' with plastic waste ratio
Figure 3. Variation of UPV with plastic waste ratio

Figure 4. Variation of $f'_c$ ratio with plastic waste ratio
The following linear relationship was obtained from regression analysis

\[ \text{UPV}\% = 98.532 - 0.4425 \text{(PW)} \]  

In which PW is the plastic waste percentage varied from 2.5% to 85%, \( R^2 \) for the above relationships is 0.75.

Fig. 6 shows variation of \( f'_c \) with UPV. One can find a poor correlation between the two properties, of \( R^2 \) equal to 0.48, mainly because different types of concrete and plastic waste have been used as stated before. Consequently, the equations proposed by the past investigators (i.e. Eqs. 1, 2 and 3 and that given by Lima (2012) has a limited application and could not be used for concrete with different plastic wastes. For this purpose, it is necessary to draw the variation of compressive strength ratio with UPV ratio. Fig. 7 shows the correlation between the two percentages. In contrast to the previous relations, there is a relatively strong correlation between the two percentages because of high \( R^2 \) which is equal to 0.91. The relation between compressive strength ratio and UPV ratio was found to be nonlinear represented by the following equation obtained from regression analysis

\[ f'_c \% = 0.0011(\text{UPV}\%)^{2.4652} \]  

Based on the above equation, the residual compressive strength of concrete containing was is calculated as follows
In which $f_{cp}'$ is compressive strength of concrete with plastic waste, $f'_c$ is compressive strength of control concrete, $UPV_p$ is ultrasonic pulse velocity of concrete with plastic waste, and $UPV_c$ is ultrasonic pulse velocity of control concrete.

Regarding of health monitoring of concrete structure, the applicability of Eq. 4 may not be of great importance, because there is a chance to perform the UPV test easily in all locations. However, Eq. 6 has a vital application to assess the variation of compressive strength with time and to diagnose any related problem. Eq. 6 can be utilized to assess the structural health against any damage via calculating the residual compressive strength $f_{cp}'$. To perform this, there is a need to measure $UPV_p$ experimentally. $UPV_c$ and $f'_c$ are related to control concrete without plastic waste. On substitution in Eq. 6, the residual compressive strength ($f_{cp}'$) is calculated. The obtained compressive strength is a tool to assess the infrastructures performance against any damage and to decide if there is a need for strengthening or not. Based on the discussion given above, the author recommends that there is a need to perform UPV test on a concrete member at the early lifetime of the structure. The existence of the early test data of $f'_c$ and $UPV$ for control concrete is helpful for the application of proposed equations for the purpose of structural health monitoring, such as Eq. 6 proposed in this study.

4. Conclusions

From the following research study, the following conclusions can be drawn

1- Analysis of a large number of test data indicates a high discrepancy of concrete compressive strength variation with plastic aggregate ratio, in which there is a high strength loss or increase at the same plastic waste content, especially at low plastic contents. Accordingly, there is a poor correlation between compressive strength of concrete and plastic aggregate content. Similarly, a weak correlation between UPV and the plastic waste content has been found. The reason of this is attributed to the fact that different plastic wastes have been tested by the past researchers.

![Figure 6. Variation of $f'_c$ with UPV](image)
There is a relatively strong correlation between UPV ratio (concrete with PW / control concrete) and plastic waste aggregate content. Eq. 4 was obtained from regression analysis to calculate this property based on plastic waste ratio.

It is more convenient to use the data of compressive strength and UPV ratios (concrete with PW / control concrete) to develop an equation for the relation between the two properties. Using regression analysis an equation was proposed (Eq. 6) to assess compressive strength of concrete based on the measurements of UPV. The proposed equation can be used to assess the residual compressive strength and to know the performance of concrete member.

It is important to perform UPV test and to have test data on control concrete at the early lifetime of the structure. The available test data is helpful for future applications of those equations proposed for the relation between compressive strength and UPV, for the purpose of structural health monitoring.

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