Correlation between destructive and non-destructive evaluation to study of plastic waste aggregate mortar: a case study of mechanical proprieties

Correlação entre avaliação destrutiva e não destrutiva para estudo de argamassa de agregados de resíduos plásticos: um estudo de caso de propriedades mecânicas

Correlación entre la evaluación destructiva y no destructiva para estudiar el mortero de áridos de residuos plásticos: un estudio de caso de las propiedades mecánicas

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ABSTRACT
Non-destructive evaluation using ultrasonic pulse velocity (UPV) testing has extensive applications in the cement materials industry. Ultrasonic pulse velocity (UPV) test is accepted as alternative to destructive testing to determine the compressive strength, dynamic modulus of elasticity, and Poisson’s ratio, which are needed for structural design. In modern construction technology, the use of Plastic Waste (PW) as a partial replacement to natural aggregates in a mortar mix is growing in popularity primarily because it reduces the initial capital cost of raw materials and the associated conservation in environment. In this regard, this study explains the correlations between mechanical proprieties, and UPV tests for mortar contains 25%, 50%, and 75% of waste aggregate of plastic. Mortar based on Plastic Waste (MPW) specimens were tested by direct, semi-direct, and indirect UPV. UPV measurements can be effectively used to determine the dynamic modulus of elasticity and Poisson’s ratio of Mortar based on Plastic Waste MPW. The dynamic elastic modulus and the Poisson’s ratio decreases for the same mortar composite when at increasing PW content. Thus, the incorporation of PW particles into the cement matrix confirms the capacity of composites to reduce the sound intensity and damp vibrations inside the composites. The results of this study will be significant for non-destructive evaluations of MPW, while additional recommendations for future studies are presented at the end of the paper.


RESUMO
A avaliação não destrutiva usando testes de velocidade de pulso ultrassônico (UPV) tem amplas aplicações na indústria de materiais cimentícios. O teste de velocidade de pulso ultrassônico (UPV) é aceito como alternativa aos testes...
destrutivos para determinar a resistência à compressão, o módulo de elasticidade dinâmico e o índice de Poisson, que são necessários para o projeto estrutural. Na moderna tecnologia de construção, a utilização de resíduos plásticos (RP) como substituto parcial de agregados naturais numa mistura de argamassa está a crescer em popularidade, principalmente porque reduz o custo de capital inicial das matérias-primas e a conservação ambiental associada. Nesse sentido, este estudo explica as correlações entre as propriedades mecânicas e os testes UPV para argamassa contém 25%, 50% e 75% de resíduos agregados de plástico. Corpos de prova de Argamassa à Base de Resíduos Plásticos (MPW) foram ensaiados por VPU direta, semidireta e indireta. As medições de UPV podem ser usadas com eficácia para determinar o módulo dinâmico de elasticidade e o índice de Poisson da argamassa com base no MPW de resíduos plásticos. O módulo de elasticidade dinâmico e o índice de Poisson diminuem para o mesmo compósito de argamassa quando aumenta o teor de PW. Assim, a incorporação de partículas de PW na matriz de cimento confirma a capacidade dos compósitos em reduzir a intensidade sonora e amortecer as vibrações no interior dos compósitos. Os resultados deste estudo serão significativos para avaliações não destrutivas de MPW, enquanto recomendações adicionais para estudos futuros são apresentadas no final do artigo.


RESUMEN
La evaluación no destructiva mediante ensayos de velocidad de impulsos ultrasónicos (UPV) tiene amplias aplicaciones en la industria de los materiales de cemento. El ensayo de velocidad de impulsos ultrasónicos (UPV) se acepta como alternativa a los ensayos destructivos para determinar la resistencia a la compresión, el módulo dinámico de elasticidad y la relación de Poisson, necesarios para el diseño estructural. En la tecnología de la construcción moderna, el uso de residuos plásticos (RP) como sustituto parcial de los áridos naturales en una mezcla de mortero es cada vez más popular, principalmente porque reduce el coste inicial de capital de las materias primas y la conservación asociada en el medio ambiente. En este sentido, este estudio explica las correlaciones entre las propiedades mecánicas, y las pruebas UPV para mortero contiene 25%, 50%, y 75% de residuos de agregados de plástico. Los especímenes de mortero a base de residuos plásticos (MPW) se ensayaron mediante UPV directo, semidirecto e indirecto. Las mediciones UPV pueden utilizarse eficazmente para determinar el módulo de elasticidad dinámico y la relación de Poisson del Mortero basado en Residuos de Plástico MPW. El módulo de elasticidad dinámico y la relación de Poisson disminuyen para el mismo compuesto de mortero al aumentar el contenido de PW. Así, la incorporación de partículas de PW en la matriz de cemento confirma la capacidad de los composites para reducir la intensidad sonora y amortiguar las vibraciones en su interior. Los resultados de este estudio serán significativos para las evaluaciones no destructivas de MPW, mientras que al final del artículo se presentan recomendaciones adicionales para futuros estudios.


1 INTRODUCTION

Although concrete is a primary material in construction, increasing world demands have led to an increase in cement production and associated undesirable increases in carbon dioxide emissions (Loke et al., 2022). Industrial waste recycling and reuse are considered important issues to face the need for a more sustainable and environmentally friendly building trade in order to obtain an appropriate management of a large quantity of by-products such as agro-food waste (Garcia; You, 2017), plastics (Badache et al., 2018, Hacini et al., 2021, Benosman et al., 2017a, Senhadji et al., 2015, Gouasmi et al., 2016, Hannawi et al., 2010, Latroch et al., 2021), batteries (Larouche et al., 2020), municipal solid waste (Asefi; Lim, 2017), and glass (Spasiano et al., 2017). Indeed, the construction industry has an extensive impact on raw materials consumption and waste production (Tavira et al., 2020, Ossa et al., 2016, Safer et al., 2024a).

Expanded PVC sheets are ideal for indoor and outdoor use in the areas of advertising, construction and industry. Expanded PVC panels are rot-proof, lightweight and rigid (Latroch et al., 2018). This material shows elastic properties, acoustic absorption, and has a good thermal resistance. Our work, which falls within this context, proposes the development of lightweight composite mortars, they are based on expanded PVC.

Numerous studies investigated different aspects of lightweight mortars or concrete in terms of fresh and mechanical properties (Almeshal et al., 2020, Latroch et al., 2023, Benosman et al., 2017b). These studies have aimed to determine the optimal replacement percentage of aggregate natural by granulates of Plastic Waste (PW), while achieving the same or greater compressive strength.

The equations for estimating the elasticity modulus and Poisson’s ratio of mortar are not included in modern building codes, despite wider applications of lightweight granulates waste of plastic (PW) (Facconi et al., 2021). An in-depth understanding of Mortar of Plastic Waste MPW’s measurement methods is
necessary because the elastic parameters data are essential for structural design (Carrillo et al., 2019). Dynamic and static elastic properties are commonly assessed using destructive and non-destructive tests. Using non-destructive testing saves time and money because the tests are quick and tested components are not damaged. The ultrasonic pulse velocity (UPV) test is widely used to evaluate concrete structures because of its ease of use, versatility, and repeatability. UPV test equipment generate a pulse that can be transmitted to concrete via a transmission and a reception transducer, thus turning mechanical energy into new impulses of the same frequency". It is possible to configure these emitter and receiver transducers in three different ways (direct, semi-direct, and indirect) (Blitz and Simpson, 1995, Najm et al., 2022, Safer et al., 2024b).

The experimental study shown in this paper includes non-destructive tests and destructive tests. WP volume in the concrete varied between 25, 50 and 75%. The recorded pulse rates allowed for calculating the values of the modulus of elasticity and Poisson’s ratio.

This paper aims to propose empirical relationships for estimating the compressive strength, modulus of elasticity, and Poisson’s ratio of Mortar Plastic Waste, using measured data of UPV tests. The results of this study can be a reference for future studies and provide wide data for Plastic Waste Aggregate Mortar based granulates waste of plastic studies.

2 MATERIALS AND METHODS

2.1 MATERIAL PROPERTIES

2.1.1 Cement

Portland cement (42.5N) was used in this research. Chemical composition of cement is shown in Figure 1. Cement was obtained from a single supplier to ensure the quality of the material is the same for all mortar mixes.
2.1.2 Sand

Silica–limestone sand was employed as natural aggregates, coming from Sidi Ali Benyoub, Sidi Bel Abbès, Algeria (Figure 1). The granulometric curve of this sand is shown in Figure 1. Its main chemical and physical characteristics are summarized in Table 1 and 2.

2.1.3 Waste from granulates waste of plastic (WP)

The waste plastic WP is a composite based expanded PVC containing a few percentage of calcite (Figure 1). It was used as a replacement for natural aggregate. The granulometric curve of this sand is shown in Figure 2. The chemical composition and physical properties of these constituents are summarised in Tables 1 and 2.

Figure 1. (a) Commercial cement; (b) natural aggregates (NA); (c) PW

Source: Authors.
Figure 2. Granulometric analysis of sand and plastic waste particles.

Table 1. Chemical composition of cement, sand and PW.

<table>
<thead>
<tr>
<th></th>
<th>Cement</th>
<th>Sand</th>
<th>PW</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>16.01%</td>
<td>SiO₂</td>
<td>28.15%</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.75%</td>
<td>Al₂O₃</td>
<td>0.15%</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.37%</td>
<td>Fe₂O₃</td>
<td>2.99%</td>
</tr>
<tr>
<td>CaO</td>
<td>60.25%</td>
<td>CaO</td>
<td>42.06%</td>
</tr>
<tr>
<td>MgO</td>
<td>1.76%</td>
<td>MgO</td>
<td>0.00%</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.26%</td>
<td>Na₂O</td>
<td>0.00%</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.46%</td>
<td>K₂O</td>
<td>0.00%</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.09%</td>
<td>TiO₂</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total chloride</td>
<td>0.03%</td>
<td>MnO₂</td>
<td>0.00%</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>CaCO₃</td>
<td>25.28%</td>
</tr>
</tbody>
</table>

Source: Authors.

Table 2. Physical properties of cement, sand and PW.

<table>
<thead>
<tr>
<th></th>
<th>Cement</th>
<th>Sand</th>
<th>WP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>3.15</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Absolute density (g/cm³)</td>
<td>2.3</td>
<td>1.400</td>
<td>0.450</td>
</tr>
<tr>
<td>Fineness Index</td>
<td>400 m²/Kg</td>
<td>Apparent density (g/cm³)</td>
<td>0.218</td>
</tr>
<tr>
<td>Normal Consistency</td>
<td>30 %</td>
<td>Equivalent of sand «%»</td>
<td>77.00%</td>
</tr>
<tr>
<td>Setting Time Initial</td>
<td>110min</td>
<td>Fineness modulus «FM»</td>
<td>2.37</td>
</tr>
<tr>
<td>Setting Time Final</td>
<td>215min</td>
<td>Coefficient of curvature «Cc»</td>
<td>1.1</td>
</tr>
<tr>
<td>Fineness (passing 45 μm)</td>
<td>95 %</td>
<td>Coefficient of uniformity «Cu»</td>
<td>5</td>
</tr>
</tbody>
</table>

Source: Authors.
2.1.4 Adjuvant superplasticizer

A water-reducing adjuvant superplasticizer, of the SIKA VISCOCRETE TEMPO 12 type, based on the acrylic copolymer, was used to ensure satisfactory workability of the various formulations.

2.2 MIXTURE PROPORTIONS

It was decided to prepare mortar based on granulates waste of plastic MPW composite samples by replacing a volume of sand by waste particles PW according to the following percentages: WP /S = 0, 25, 50 and 75%, where PW represents the amount of granulates waste of plastic aggregates and S the amount of sand. A superplasticizer was used to control the fluidity of the mixtures. The mortar was prepared according to the following proportions: 1 part of cement, 3 parts of sand and a constant water to cement ratio (W/C = 0.5) for all formulations (Standard, 2005). Details of the composition of the combinations are given in Table 3.

<table>
<thead>
<tr>
<th>Composites</th>
<th>WP (%)</th>
<th>WP (Kg/m³)</th>
<th>SP*** (%)</th>
<th>Cement (Kg/m³)</th>
<th>Water (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM</td>
<td>0</td>
<td>0.00</td>
<td>1.00</td>
<td>450.00</td>
<td>0.50</td>
</tr>
<tr>
<td>MPW 25</td>
<td>25</td>
<td>44.90</td>
<td>0.80</td>
<td>450.00</td>
<td>0.50</td>
</tr>
<tr>
<td>MPW 50</td>
<td>50</td>
<td>89.90</td>
<td>0.60</td>
<td>450.00</td>
<td>0.50</td>
</tr>
<tr>
<td>MPW 75</td>
<td>75</td>
<td>134.70</td>
<td>0.45</td>
<td>450.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Source: Authors.

*: Substitution of sand by volume of PW.
***: Percentage of superplasticizer admixture relative to the weight of cement.

2.3 MIXING PROCEDURE

The mortars and/or composites were cast in prismatic molds (4× 4 × 16 cm³) and mechanically compacted using an electric shock table NF EN 196-1 (Standard, 2005). According to the NF EN 196-1, the mortar specimens were kept in their moulds for 24 h after mixing and then cured in water at a constant temperature of 20 °C until test. The test age of the specimen is 7, 14, and 28 days and the specimens were taken out of water for UPV testing for less than an hour during the curing days.
2.4 TEST PROCEDURE

2.4.1 Compression test

Compressive strength tests were performed (using a Baldwin universal testing machine) on cube samples in accordance with ASTM C109-21 (Standard, 2013) after curing periods of 7, 14 and 28 days. Tests were performed on three specimens for each mix at a constant displacement rate of 0.5 mm/min.

2.4.2 Ultrasonic Pulse Velocity (UPV)

The UPV (direct, semi-direct, and indirect) (Figure 3, 4, and 5) technique is one of the widely used and convenient methods that can provide test results at the lowest cost and rapid measurements. The testing complied with several established standards such as ASTM C597-02 (C597-97, 1997), BS 1881-203:1986 (Standard, 1881).

Figure 3. Direct UPV measurement.

Source: Authors.

Figure 4. Semi-direct UPV measurement.

Source: Authors.
3 POISSON’S RATIO AND DYNAMIC ELASTIC MODULUS

The definition of Poisson’s ratio is the negative ratio of the relative axial strain to the strain in the direction of the applied force (Haktanır et al., 2002). Generally, including cementitious and concrete materials, the Poisson’s ratio for most materials varies between 0 and 0.5. Assuming the specimen is compressed along the axial direction, the Poisson’s ratio can be calculated as in Equation (1). For isotropic material, the relationship of shear modulus, Poisson’s ratio, and elasticity modulus can be shown in Equation (2).

\[ v = \frac{d \varepsilon_{\text{trans}}}{d \varepsilon_{\text{axial}}} \]  \hspace{1cm} (1)

\[ G = \frac{E}{2(1+v)} \]  \hspace{1cm} (2)

where:

- \( v \) is Poisson’s ratio,
- \( \varepsilon_{\text{trans}} \) is transverse strain,
- \( \varepsilon_{\text{axial}} \) is axial strain,
- \( G \) is shear modulus (GPa),
- \( v \) is Poisson’s ratio, and
- \( E \) is elasticity modulus (GPa).

The dynamic elastic modulus (Ed) and Poisson ratio (\( v \)) can be calculated using the velocity by direct measurement of UPV. Existing relationships to...
determine properties by wave velocity are presented as in Equations (3)-(4) (Najm et al., 2022):

\[ E_d = \frac{UPV^2 \rho}{g} \times 10^{-2} \] \hspace{1cm} (3)

\[ UPV = \frac{E_d}{\sqrt{2 \rho (1+v)}} \] \hspace{1cm} (4)

where:

- \( E_d \) is dynamic elastic modulus (GPa),
- \( \rho \) is density (kg/m\(^3\)),
- \( UPV \) is direct ultrasonic pulse velocity (km/s),
- \( v \) Poisson' ratio .

4 RESULTS AND DISCUSSION

4.1 MECHANICAL COMPRESSIVE STRENGTH

Compressive strength was measured at 7, 14, and 28 days as shown in Figure 6. The compressive strength of MPWs will increase with the time from 7 days to 28 days, which agrees with existing knowledge. The specimen, which contains 75% of WP, shows the lowest strength in 7, 14 and 28 days compared to all other specimens. The compressive strength decreases with the increase of the WP content in the composite; this is probably due to the weak bond between the WP aggregates and the cement paste. Similar results had been reported on composite mortars based on light recycled aggregates by (Herki; Khatib, 2017, Dulsang et al., 2016, Hannawi et al., 2010).
4.2 ULTRASONIC PULSE VELOCITY (UPV) TEST

4.2.1 Direct UPV measurements

It is stated that when the compressive strength increases, the UPV increases. The UPV result follows approximately the same pattern for each kind of MWP at a given test age as shown in Figure 7. It was found that UPV decreases as the amount of PW aggregates increases in all mixtures after 7, 14 and 28 days. It was also noted that the percentage of decrease in UPV with respect to the NM control mortar, rose up from 3%, 4%, and 5% for the composites MPW25, MPW50 and MPWC75, respectively at 28 days. However, UPV measured in normal mortar NM shows that the difference between UPV in comparison to MPW is significant as shown in Figure 8. The difference in UPV between normal mortar NM and MPW is approximately 3% to 7%. In general, the UPV results of NM at exceed 3800 m/s at 28 days, which declares that the quality of mortar is good.
The UPV can determine the quality of mortar, as shown in Table 4. as a function of UPV. Several factors can affect the compressive strength of concrete and some of those factors influence the UPV. The relationship between these variables and the UPV will be investigated in this study. These variables are:
1. age of mortar (3, 7, and 28 days); 
2. testing procedure (direct, semi-direct, and indirect UPV test); 
3. WP percentage (25, 50, and 75%).

Table 4. Quality of mortar given by IS code (BS, 1881, 1983) (Standard, 2005).

<table>
<thead>
<tr>
<th>UPV (m/s)</th>
<th>Mortar quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4500</td>
<td>Excellent</td>
</tr>
<tr>
<td>3500 to 4500</td>
<td>Good</td>
</tr>
<tr>
<td>3000 to 3500</td>
<td>Medium</td>
</tr>
<tr>
<td>&lt;3000</td>
<td>Doubtful</td>
</tr>
</tbody>
</table>

Source: Authors.

According to Figure 9, the compressive strength $R_c$ (MPa) varies with the UPV of the (m/s) according to the expression: $UPV = 0.85 \, R_c^2 - 44.48 \, R_c + 4146.8$, with a correlation coefficient $R^2 = 0.943$. This value indicates that the compressive strength has a higher correlation with the direct UPV of the MPW mortars.

Figure 9. Correlation between the compressive strength and UPV, after 28 days.

Source: Authors.

4.2.2 Semi-direct UPV measurements

Figure 10 shows the semi-direct UPV measurements in all specimens at the age of 7, 14 and 28 days. The UPV in MPW and plain concrete at 28 days has a significant difference. From a curing period of about one week onwards, the MPW
mortar mixtures with 75% PW replacement show a lower rate of UPV development with time compared to the mixes with 25% and 50% MPW replacements.

Figure 10. Semi-direct UPV measurements at 7, 14 and 28 days.

Source: Authors.

Figure 11. Correlation between the compressive strength and semi-direct UPV, after 28 days.

\[ y = 1.09x^2 - 52.01x + 4115.4 \]

\[ R^2 = 0.6805 \]

Source: Authors.

According to Figure 11, the compressive strength Rc (MPa) varies with the UPV of the (m/s) according to the expression: \( UPV = 1.09 R_c^2 - 52.01 R_c + 4115.8 \), with a correlation coefficient \( R^2 = 0.6805 \). This value indicates that the compressive strength has a medium correlation with the semi-direct UPV of the MPW mortars. Hence, to use the semi-direct method, it is very effective to gather a large number of UPV data and statistical analysis to make sure the results are reliable.
4.2.3 Indirect UPV measurements

Figure 12 shows indirect UPV measurements for all the specimens at 7, 14 and 28 days of age. It can be found that the UPV will increase for the different path lengths of the beam with increasing age.

Figure 12. UPV indirect measurements at 7, 14 and 28 days.

At the 50% substitution rate, the ultrasonic pulse wave velocities of the 7, 14, and 28 days, mortar reached their maximum at 3400 m/s, 3500 m/s and 3800 km/s, respectively. The velocity of ultrasonic pulses is influenced by the medium, and their propagation speeds in solids are higher than those in liquids and air. The pulse velocity of the mortar ranged from 3200 to 3600 m/s for 7 days and 3700 to 3900 m/s for 28 days, indicating that the age of the mortar had a significant effect on the ultrasonic pulse velocity.
As shown in Figure 13, there was a certain correlation between the propagation speed of ultrasonic waves in MPW mortars and their compressive strength according to the expression: \( \text{UPV} = 0.23 \cdot \text{Rc}^2 - 3.96 \cdot \text{Rc} + 3675.8 \), with a correlation coefficient \( R^2 = 0.8028 \).

### 4.3 COMPARATIVE RELATIONSHIPS OF DIRECT, SEMI-DIRECT, AND INDIRECT MEASUREMENTS WITH THE COMpressive STRENGTH

The different correlations between the types of UPV Measurement and compressive strength of MPW mortars at 28 days are given in Table 5. Equations of semi and indirect UPV have a poor \( R^2 \) value compared to \( R^2 \) values for the correlations for direct UPV measurement with the compressive strength. The high value of \( R^2 \) indicates that a good estimate of the compressive strength is through the direct UPV measurement.

<table>
<thead>
<tr>
<th>UPV Measurement</th>
<th>Correlation equation</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>( \text{UPV} = 0.85 \cdot \text{Rc}^2 - 44.48 \cdot \text{Rc} + 4146.8 ), ( R^2 = 0.9431 )</td>
<td></td>
</tr>
<tr>
<td>Semi-direct</td>
<td>( \text{UPV} = 1.09 \cdot \text{Rc}^2 - 52.01 \cdot \text{Rc} + 4115.8 ), ( R^2 = 0.6805 )</td>
<td></td>
</tr>
<tr>
<td>Indirect</td>
<td>( \text{UPV} = 0.23 \cdot \text{Rc}^2 - 3.96 \cdot \text{Rc} + 3675.8 ), ( R^2 = 0.8028 )</td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors.
4.4 POISSON’S RATIO AND DYNAMIC ELASTIC MODULUS

The UPV will change with the different properties of concrete such as its elastic stiffness and mechanical strength. Therefore, the UPV test can be used to determine Poisson’s ratio and modulus of elasticity of FRC. By the use of equations, the dynamic elastic modulus and Poisson ratio for different MPW mortar. In Table 6, results for the UPV tests of the MPW mortar are presented. It can be easily found that the modulus of elasticity and Poisson’s ratio increase with the age of the mortar. The modulus of elasticity of MPW25, MPW50 and MPW75 is 30.27 GPa, 29.22 GPa, and 26.36 GPa at 28 days, respectively. The Poisson’s ratio of normal mortar is between 0.100 and 0.200. According to the test results, the mortar Poisson’s ratio is between 0.082 and 0.1488, which is consistent with the general mortar Poisson’s ratio.

<table>
<thead>
<tr>
<th>Age (Days)</th>
<th>MPW mortar</th>
<th>UPV (Km/s)</th>
<th>Density (Kg/m³)</th>
<th>Modulus of Elasticity, Ed (GPa)</th>
<th>Poisson’s Ratio, v</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>NM</td>
<td>3.10</td>
<td>2329</td>
<td>22.81</td>
<td>0.106</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>3.38</td>
<td>2201</td>
<td>25.63</td>
<td>0.113</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>3.77</td>
<td>2258</td>
<td>32.78</td>
<td>0.148</td>
</tr>
<tr>
<td>7</td>
<td>MPW25</td>
<td>3.30</td>
<td>2189</td>
<td>24.30</td>
<td>0.106</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>3.55</td>
<td>2160</td>
<td>27.74</td>
<td>0.120</td>
</tr>
<tr>
<td>28</td>
<td></td>
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<td>2232</td>
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Source: Authors.

Figure 14 shows the dynamic elastic modulus and Figure 15 shows the Poisson’s ratio of MPW at 28 days. The modulus of elasticity and Poisson’s ratio decreases with the increasing of PW.
5 CONCLUSIONS

This study demonstrated the effect of partial replacement of natural aggregate with plastic waste PW in mortar with ratios (25, 50, and 75%). In this paper, empirical results have been developed using the ultrasonic pulse velocity (UPV) test to estimate the values of the modulus of elasticity and Poisson’s ratio of mortar based on plastic waste MPW. The results of the study showed that it is
essential to select the setup of the non-destructive test that should be applied (direct, semi-direct, and indirect) for detecting the compressive strength. Based on the research results, the following conclusions were drawn:

1. the partial replacement of sand by aggregates of plastic waste PW contributes to reducing the specific weight of MPW composites compared to that of the control mortar;

2. with increasing plastic waste PW content, the compressive strength of the MPW mortar first increased and then decreased;

3. the volume of plastic waste PW seems ineffective in increasing the UPV. However, plastic waste PW can slightly decrease the UPV measurements by 3%, 4%, and 5% for the composites MPW25, MPW50 and MPWC75 at the age of 28 days, respectively, in comparison to the control mortar NM;

4. the UPV and compressive strength of MPW have a significant difference at an early age of mortar. Both UPV and compressive strength decrease when the plastic waste PW content increases;

5. the Accuracy of UPV from largest to smallest is direct UPV, semi-direct UPV, and indirect UPV, respectively. The correlation coefficient $R^2$ obtained between direct UPV and compressive strength using the regression formula was 0.941. Establishing a regression equation can provide a technical reference for detecting the strength of MPW mortars, using the direct ultrasonic method. The accuracy of semi-direct UPV is relatively lower;

6. the ratio between density and direct UPV can be used to determine the dynamic modulus of elasticity and Poisson’s ratio of the mortar. If plastic waste PW content increases, the dynamic elastic modulus and the Poisson’s ratio decrease, decrease for the same pace;

The incorporation of plastic waste PW into mortar confirms the capacity of composites to both reduce the sound intensity and damp vibrations inside the composites, thus achieving a good level of acoustic insulation. The reduction in the dynamic elastic modulus can be considered as potentially beneficial for some applications, such as sidewalks, for example. Thus, composites, containing PW aggregates, have much better thermal insulation properties than those of unmodified mortars. These composites could be the subject of multiple applications; they can be used to slow down or prevent the heat transfer and therefore to save energy.
FUTURE PERSPECTIVES

Continuing along this research trajectory opens up exciting perspectives. Furthermore, analyzing remaining durability parameters such as air permeability, carbonation, chloride ion penetration, and chemical attacks would provide new insights into the long-term resilience of these materials. These studies take into account economic, sociological and ecological considerations; they constitute an interesting work of the impacts of the installation of plastic waste on the cementitious materials.
REFERENCES


