Mechanical and Thermal Performances of Eco-Friendly Mortar Containing Recycled PET As Partial Sand Replacement

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Mechanical and thermal performances of eco-friendly mortar containing recycled PET as partial sand replacement

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Graphical abstract:

![Graphical Abstract Image]

Abstract:

Plastic has become one of the most widely manufactured materials in the world and an indispensable part of everyday life. However, a large amount of plastic waste needs to be recycled to protect the environment. One way of recycling is to use such waste as a raw material substitute. This paper evaluates the thermal and mechanical performance of eco-friendly mortars containing 0%, 5%, 10%, 15% and 20% recycled polyethylene terephthalate (PET) particles as partial replacements for sand. Several experiments were conducted to evaluate the thermal properties (i.e. thermal conductivity, thermal diffusivity and heat capacity), compressive strength, density, workability and ultrasonic pulse velocity of these mortars. Results show that replacing sand with recycled PET in cement-based mortars reduces their thermal conductivity, thereby highlighting the potential use of these mortars as energy-efficient and environmentally friendly construction materials.
Keywords: Thermal conductivity; Thermal diffusivity; Heat capacity; Recycled PET; Eco-friendly mortar; Plastic bottles.

1. Introduction

Polyethylene terephthalate (PET) is one of the most commonly used waterproof materials in packaging, fibres and other fields. PET bottles are not only known for their light weight, high strength and low gas permeability (mainly \( \text{CO}_2 \)) but also for their aesthetic appearance, good light transmission and smooth surface (Miranda et al. 2017). These bottles also have a good price–performance ratio and excellent properties, such as their high durability, good mechanical and electrical properties and low production cost (Reis et al. 2011; Welle 2011; Reis and Carneiro 2012; Fraternali et al. 2014). The use and production of PET bottles have grown rapidly since the 1970s after the introduction of blow moulding technology (W.Glenz 2007). A total of 580 billion PET bottles are expected to be produced and consumed globally in 2021, which can serve about 80% of the total water packaging demand (Tamburini et al. 2021). However, the increasing demand for these bottles generates a huge amount of plastic waste that negatively affects the environment. Although PET is a recyclable material, not all generated waste can be recycled immediately. These wastes are either landfilled (thereby requiring large areas of land for storage) or dumped into streams, rivers and seas. The elimination of these wastes poses a considerable threat to the environment due to their poor degradation (Li et al. 2020). Therefore, reusing PET bottles contributes to protecting the environment (i.e. by reducing energy consumption and pollution, recycling plastic waste and preserving natural resources) and addressing the sources of environmental pollution (e.g. oil industry) (Colangelo et al. 2016). Government organisations and environmental activists consider the recycling of plastic waste as the first societal challenge that must be addressed to solve problems related to environmental pollution (Basha et al. 2020). In 2018, about 32.5% of the plastic waste collected in Europe was recycled, whereas the rest was either incinerated or used as fuel (energy source) (PlasticsEurope 2020).

Scientists have recently shown interest in using plastic waste as construction materials given its positive technical and financial impacts (Kou et al. 2009; Akçaözoğlu et al. 2010; Batayneh et al. 2007; Almeshal et al. 2020b; Górak et al. 2021). Plastic waste can be used as a replacement aggregate in either coarse or fine forms. Mohammed (2017) observed that after adding 5% PET waste, the compressive strength of concrete significantly decreases even after the classification of the PET waste particles. He then concluded that using concrete with up to 15% PET waste is safe for the fabrication of reinforced concrete beams. Al-Tayeb et al. (2017) reported that the workability, compressive stress, tensile stress-splitting and modulus of elasticity of plastic concrete decrease along with increasing plastic content. However, the ultimate fracture impact strength increases after the addition of plastic due to the flexibility brought by plastic to the mix. Aldahdooh et al. (2018) studied the compressive strength and workability of plastic concrete with regular and irregular particle plastic waste aggregates and found that the workability of regular particle plastic waste concrete is worse than that of irregular particle plastic waste concrete and that its optimum compressive strength at 28 days was only 24% of irregular particle plastic waste. Almeshal et al. (2020) studied how partially replacing sand with PET waste affects the fresh weight of the mix, the quality of the concrete and its fire behaviour. They found that increasing the PET replacement rate in concrete reduces the fresh weight values of the mix below the reference, the ultrasonic impulse velocity (which reflects the quality of the concrete) and the fire resistance of the concrete; moreover, the addition of PET emits an unpleasant toxic smoke. Steyn et al. (2021) examined the performance of concrete with waste plastic, rubber and glass as fine...
aggregates at 15% and 30% replacement proportions and found that the addition of rubber and plastic leads to poor
durability and stiffness whereas the addition of glass improves durability and stiffness. By contrast, the concrete
with low plastic content has a compressive strength comparable to that of the reference mix but shows inferior
tensile performance, whereas the concrete with rubber demonstrates inferior compression and flexion at both high
and low contents. In sum, plastic waste can be used to produce building materials with acceptable engineering
properties.

This paper then investigates the compressive strength and thermal performance of mortars containing 0%, 5%,
10%, 15% and 20% crushed recycled PET particles as partial replacements for sand. The correlation between the
mechanical and thermal properties of the concrete was also evaluated. This study aims to develop and promote the
use of sustainable and ecological mortars in thermal insulation.

2. Materials and methods

2.1. Materials

2.1.1. Binder

For the binder, this study uses a local composite Portland cement (type CPJ 45) provided by Holcim and
conforming to the Moroccan standard NM10.1.004. This cement was chosen because of its abundant use in the
construction field in Morocco. Table 1 summarizes its chemical and physical properties

| Chemical composition (%) | Physical properties of cement |
|--------------------------|------------------------------|
| SiO$_2$                  | 21.3 Specific gravity        |
| Al$_2$O$_3$              | 5.58 Blaine specific area (m$^2$/kg) |
| FeO$_3$                  | 3.4                          |
| CaO                      | 62 Blaine specific area (m$^2$/kg) |
| MgO                      | 1.85                         |
| K$_2$O                   | 2.1 Initial setting time (min) |
| TiO$_2$                  | 0.3                          |
| SO$_3$                   | 2.41 Final setting time (min)  |

2.1.2. Water

The drinking water from Rabat’s Intercommunal Autonomous Water and Electricity Distribution Authority
(REDAL) was used to mix the mortars. The physical and chemical characteristics of this water satisfy the
requirements of NM 10.1.353.
2.1.3. Sand

The mortars were manufactured using sea sand collected from the Kenitra region. **Table 2** presents the experimental results for this sand, and **Fig. 2** illustrates its granulometric composition.

**Table 2: Sand characteristics**

| Characteristic                        | Value    | Standard  |
|--------------------------------------|----------|-----------|
| Sand Equivalent (ES) (%)             | 92.53    | NF EN 933-8 |
| Fineness modulus (FM)                | 2.8      | NF EN 933-1 |
| Absolute density (g/cm³)             | 2.46     | NF EN-1097-6 |
| Apparent density (g/cm³)             | 1.29     | NF EN-1097-7 |

2.1.4. Recycled PET

The PET used as partial replacement for sand in a cement-based mortar (**Fig. 1**) was recycled from washed and crushed PET bottles and had a maximum particle size of 7 mm. **Fig. 2** illustrates the results of the particle size analysis. The formulation and characterisation of the cementitious mortar with and without PET follows the methodology described in **Fig. 3**.

**Fig. 1: PET used in cement-based mortar**
2.2. Preparation and samples conditioning

Five replacement ratios were applied to determine the effect of PET on the mechanical and thermal properties of cement mortar following the procedures described in NF EN 196-1. In the mortar compositions, natural sand was systematically replaced with 0%, 5%, 10%, 15% and 20% PET particle mass as shown in Table 3. A constant water/cement (W/C) ratio of 0.5 was observed when producing the mortars.
Prismatic samples of (40 40 160) mm and (40 80 120) mm were made for each mix. A day after casting, the (40 40 160) mm prismatic specimens were stored in water at 21±1 °C, and the (40 80 120) mm specimens were stored in ambient air until reaching the test age.

| Mix. ID | Replacement percentage (%) | Cement (g) | Sand (g) | PET (g) | Water (W/C=0.5) (g) |
|---------|-----------------------------|------------|---------|--------|---------------------|
| PET-0   | 0%                          | 450        | 1350    | 0      | 225                 |
| PET-5   | 5%                          | 450        | 1282.5  | 67.5   | 225                 |
| PET-10  | 10%                         | 450        | 1215    | 135    | 225                 |
| PET-15  | 15%                         | 450        | 1147.5  | 202.5  | 225                 |
| PET-20  | 20%                         | 450        | 1080    | 270    | 225                 |

Table 3: Mix proportions of mortars.

2.3. Methods

2.3.1. Workability

Workability was evaluated by using a mini-cone immediately after 5 min of mixing. This device was developed by Wedding and Kantro (1980) and consists of measuring at 20 °C the mini-cone of the mortar in a truncated cone-shaped mold, 60 mm high with diameters of 70 mm at the top and 100 mm at the base (d₀).

2.3.2. Density

The density of the eco-friendly mortar containing recycled PET as partial sand replacement was measured at 28 days according to ASTM C642.

2.3.3. Ultrasonic pulse velocity

Following ASTM C597-16, ultrasonic pulse velocity was measured by direct transmission using the portable ultrasonic non-destructive digital indicating tester, which assesses the quality of concrete and checks for the presence of voids. This test was also extended to include a wide range of concrete properties, including durability (Lafhaj et al. 2006). The ultrasonic pulse velocity in the eco-friendly mortar samples was calculated as

\[ V_p = \frac{L}{\Delta t} \]  

where \( V_p \) is the ultrasonic pulse velocity (m/s), \( L \) is the distance (m) and \( \Delta t \) is the transit time (s).

2.3.4. Mechanical characterisation

The compressive strength of the mortars was measured according to NF EN 196-1 in a compression testing machine by applying a load force on the prismatic specimens (40 40 160) cm in the direction perpendicular to the casting axis until rupture. The compressive strength of the mortars was computed as the arithmetic mean of the measured values for three specimens. The machine used had a precision of about 1%.

2.3.5. Thermophysical characterisation

The thermal properties of cement-based materials can be determined either in a steady or transient state (Liu et al. 2014; Li et al. 2016; Asadi et al. 2018). While steady-state methods are used most often, they usually have a long application time (two to three hours per sample) as they require the temperature gradient on a sample to be stable (Mirzamamadi et al. 2018). By contrast, transient methods can measure thermal conductivity, thermal diffusivity...
heat capacity within a few minutes due to their ability to record temperature signals during the heating process without requiring a thermal equilibrium state (Liu et al. 2014; Li et al. 2016). One transient method is the transient planar source method (TPS) developed by Gustafsson (1991), which has attracted increasing interest because of its high accuracy (within ± 5%), applicability to a wide range of tests (e.g. with thermal conductivity of 0.005 W/mK to 1800 W/mK) and high speed (only a few minutes per sample). Given the various advantages of TPS, a TPS 1500 hot disc instrument and a Kapton 5501 sensor with a radius of 6.4 mm (Fig. 4) were used in this study to measure the thermal properties of eco-friendly mortars. The TPS 1500 hot disc instrument measures the thermal properties of solid, liquid, powdery and pasty materials according to ISO 22007-2. Coating the sample or adding a substance for improving thermal contact is unnecessary in the measurements. The Kapton sensor has a double electrically conductive spiral etched on a nickel foil and two thin layers of Kapton insulating material covering the surfaces of the nickel foil. The Kapton sensor is sandwiched between two samples with dimensions of 40×80×120 mm, acting both as a heat source and a temperature sensor that records the increase in temperature as a function of time. As shown in Equation (2), the average temperature increase (ΔT̅) can be expressed as a function of thermal conductivity (k), collector radius (r), heating power (P₀) and a specific dimensionless time function D(𝜏) (Gustafsson 1991). D(𝜏) is formulated as Equation (3), where I₀ is the modified Bessel function, m is the number of concentric rings on the sensor and τ is a function of thermal diffusivity (α), measurement time (t) and sensor radius (r) as shown in Equation (4)(Gustafsson 1991; Liu et al. 2014). The thermal diffusivity and conductivity of the samples are unknown parameters that can be calculated by using an integrated software after a series of iterations. The volumetric heat capacity (ρC_p), which is defined as the product of specific heat capacity (C_p) and density (ρ), can be calculated using Equation (5)(Liu et al. 2014).

\[ ΔT̅ = \frac{P₀D(τ)}{\frac{3}{2}πrK} \]  
\[ D(τ) = \frac{1}{m²(m + 1)²} ∫_0^τ dσ \sum_{i=1}^{m} \sum_{j=1}^{m} kexp\left(-\frac{(i² + j²)}{4m²σ²}\right) × I₀\left(\frac{ij}{2m²σ²}\right) \]  
\[ τ = \frac{\sqrt{αt}}{r} \]  
\[ ρC_p = \frac{K}{α} \]  

The specimens for TPS testing were prepared and tested as follows. Firstly, three pairs of specimens with dimensions of 40×80×120 mm were prepared and cured for 28 days for each test. Secondly, the specimens were oven dried at 105 °C for 24 hours to remove moisture following the usual practice in previous studies(Khan 2002; Uysal et al. 2004; Liu et al. 2011; Sengul et al. 2011; Liu et al. 2014; Wu et al. 2015; Real et al. 2016). Given that the moisture content of cement mortars significantly affects their thermal properties(Khan 2002; Real et al. 2016; Asadi et al. 2018), the moisture must be eliminated due to its significant variation (ranging from 7.6% to 28% for different aggregate replacement rates as reported by in wo measurements were conducted on each pair of samples.
3. Results and discussion

3.1. Workability

The results for the mini-slump of eco-friendly mortars are presented in Fig. 5. Increasing the proportion of recycled PET improves the fluidity of mortar due to the fact that recycled PET particles have a lower water absorption and smoother outer surface compared with sand, thereby reducing the friction between the particles and mortar and increasing the presence of free water. Similar to other studies, the slump value increased along with the amount of plastic in the mix (Choi et al. 2005; Saikia and de Brito 2012; Sharma and Bansal 2016; Almeshal et al. 2020b). The improved workability can also be ascribed to the shape and size of the PET particles, which is consistent with the findings of Saikia and Brito (Saikia and de Brito 2014).

![Fig. 5: Mini-slump of eco-friendly mortars](Image)

3.2. Density

Fig. 6 presents the influence of recycled PET on the density of eco-friendly mortars. The rate of partially replacing sand with recycled PET significantly influenced the density of the specimens. The average density values decreased from 2177±15 kg/m$^3$ to 2135±30, 2109±24, 2080±26 and 2049±22 kg/m$^3$ after increasing the partial sand replacement rate from 0% to 5%, 10%, 15% and 20%, respectively. (yazoghli et al. 2005; Saikia and de Brito 2014; Almeshal et al. 2020a) ascribed such decrease to the lighter specific gravity of the plastic aggregate compared with that of fine or coarse natural aggregate. Using light aggregates as cement-based building materials...
is generally preferred in building construction as they can reduce the load on building foundations and structures, thereby facilitating construction and reducing costs (Lo et al. 2007).

Fig. 6. Density of eco-friendly mortars at day 28

3.3. Ultrasonic Pulse Velocity

The effect of PET addition on the porosity of mortars was evaluated via ultrasonic measurements as shown in Fig. 7. Those mortars containing recycled PET cured at 23 °C had a UPV value of 2575±6 m/s, which decreased to 2390±10, 2241±14, 2124±19 and 2001±34 m/s after increasing the partial sand replacement rate from 0% to 5%, 10%, 15% and 20%, respectively, thereby confirming the findings in Section 3.2. Meanwhile, reducing the mortar compactness also reduced the ultrasonic wave velocity yet increased the void content of the mortar (Akcaozoglu et al. 2013). Previous studies have shown that the ultrasonic pulse velocity wave passing through air voids is lower than that passing through solid materials (Ikpong 1993; Bogas et al. 2013). Therefore, the UPV decreases due to the replacement of sand with PET. The same results have been reported in other research (Albano et al. 2009; Correia et al. 2014; Aldahdooh et al. 2018; Almeshal et al. 2020b; Almeshal et al. 2020a).

Fig. 7. Ultrasonic pulse velocity of mortars containing recycled PET
3.4. Compressive strength

As shown in Fig. 8, the compressive strength of eco-friendly mortars decreased along with an increasing partial replacement rate of sand with recycled PET. For example, significant strength reductions of 11.28% and 26.6% were observed after 28 days with a W/C ratio of 0.5 and replacement rates of 5% and 20%, respectively.

Such decrease in strength was mainly ascribed to the low cohesion between the texture and recycled PET, which acts as a barrier that prevents the cement paste from adhering to natural aggregates. Therefore, friction was not significant, and the compressive strength gradually decreased along with an increasing addition of PET. This phenomenon may also be ascribed to the different properties (e.g. size and shape) of the recycled PET used in the mortar. The same results have been reported in the literature (Saikia and de Brito 2012; Ge et al. 2013; Al-Tayeb et al. 2017; Aldahdooh et al. 2018; Almeshal et al. 2020a; M. Al-Tayeb et al. 2021).

The 28-day compressive strength of mortars containing recycled PET was correlated with density and UPV values as shown in Fig. 9. The compressive strength decreased along with density and UPV values. Such correlation was ascribed to the fact that both density and UPV values are closely related to the voids introduced by recycled PET. Previous studies have also reported similar relationships, such as the correlation between unconfined compressive strength (UCS) and density (Liu et al. 2014; Asadi et al. 2018) and that between UCS and UPV (Bogas et al. 2013; Wu et al. 2016) for ordinary Portland cement (OPC)-based mixes.

Fig. 8. Compressive strength of mortars containing recycled PET at day 28

Fig. 9: Correlation between (a) density and compressive strength and (b) UPV and compressive strength
3.5. Thermophysical characterisation

3.5.1. Thermal conductivity

As shown in Fig. 10, the partial replacement rate of sand with recycled PET significantly affected the thermal conductivity of mortars containing recycled PET. The 28-day thermal conductivity of mortars containing recycled PET decreased from 1.303±0.036 W/mK to 1.064±0.049, 0.917±0.086, 0.804±0.099 and 0.693±0.096 W/mK when the partial sand replacement rate increased from 0% to 5%, 10%, 15% and 20%, respectively. Such reduction can be ascribed to the low thermal conductivity of PET (~0.15 W/mK) and the thermal conductivity of sand (between ~1.16 W/Mk and 8.6 W/Mk)(Akçaözoğlu et al. 2013; Asadi et al. 2018). The difference between the thermal conductivity of recycled PET and sand decreased the thermal conductivity of mortars containing recycled PET as the partial sand replacement rate increased. In practice, a lower thermal conductivity benefits cementitious building materials by attenuating the intensity of thermal conduction and reducing heat loss to the external environment, thereby decreasing the energy consumption and CO$_2$ emissions related to the heating and cooling of buildings(Latha et al. 2015; Asadi et al. 2018).

Thermal conductivity was correlated with density and UPV, respectively, as shown in Fig. 11. An exponential correlation with a coefficient of 0.999 and a pre-exponential factor of 0.00003 was observed between thermal conductivity and density as shown in Fig. 11 (a). Meanwhile, Fig. 11 (b) shows that thermal conductivity increases exponentially with UPV. The favourable correlations between thermal conductivity and density and between thermal conductivity and UPV values highlight the feasibility of estimating the thermal conductivity of mortars containing recycled PET from the densities or UPV values. This method of using UPV value to estimate thermal conductivity is also non-destructive.

![Fig. 10. Thermal conductivity of mortars containing recycled PET](image-url)
3.5.2. Volumetric heat capacity

Volumetric heat capacity refers to the heat required to change the unit temperature of one unit volume of a material. Fig. 12 shows the influence of partial sand replacement rate on the volumetric heat capacity of mortars containing recycled PET. As shown in Fig. 12, increasing the partial sand replacement rate reduced the volumetric heat capacity. The 28-day volumetric heat capacity of mortars containing recycled PET decreased from 1.537±0.12 MJ/m³K to 1.52±0.29, 1.352±0.24, 1.153±0.37 and 0.942±0.13 MJ/m³K as the partial sand replacement rate increased from 0% to 5%, 10%, 15% and 20%, respectively. Fig. 13 shows that the volumetric heat capacity of mortars containing recycled PET can be expressed as a function of density or UPV. The volumetric heat capacity of mortars containing recycled PET increased along with density or UPV. However, the correlation between volumetric heat capacity and density or UPV has rarely been reported in the literature. Oktay et al. (2015) reported a similar increase in volumetric heat capacity with increasing bulk density after converting specific heat capacity into volumetric heat capacity.
3.5.3. Thermal diffusivity

Thermal diffusivity is the rate at which the temperature of a material varies in response to external thermal stress, which in turn is expressed as thermal conductivity divided by density and specific heat capacity. This characteristic is critical to guarantee good comfort, especially during summer (i.e. to prevent overheating). **Fig. 14** shows a reduction in thermal diffusivity without any clear trend regarding the influence of sand replacement rate. For example, the 28-day thermal diffusivity of recycled PET-based mortars decreased from 0.848 mm²/s to 0.700, 0.678, 0.697 and 0.736 mm²/s as the sand replacement ratio increased from 0% to 5%, 10%, 15% and 20%, respectively. The reduction in thermal diffusivity was attributed to the heterogeneity of the recycled PET-based mortars (with many pores and voids) through which heat propagates by conduction, convection and radiation at the same time. This result has also been reported in the literature where thermal diffusivity decreases along with increasing pore and void volume (Oktay et al. 2015; Hassn et al. 2016).

**Fig. 15** shows the polynomial correlation of thermal diffusivity with density and UPV values with correlation coefficients of 0.9814 and 0.9834, respectively. The thermal diffusivity of recycled PET-based mortars decreased exponentially along with decreasing density or UPV. These correlation trends have also been reported for OPC-based mixtures in previous studies (Liu et al. 2014; Oktay et al. 2015).
Fig. 15: Correlation between (a) density and thermal diffusivity and (b) UPV and thermal diffusivity

4. Conclusion:

This study examined how the replacement of sand with recycled PET in cement-based mortars could affect the mechanical and thermophysical properties of the mix. The following conclusions were drawn:

1. Replacing sand with recycled PET tends to increase the workability of the mix due to the low water absorption and smoother outer surface of the latter compared with the former, thereby enhancing workability at a constant water content.

2. After 28 days of curing the eco-friendly mortar containing recycled PET as a partial replacement for sand, PET-20 demonstrated a 38% lower density (2049 kg/m³) compared with PET-0. Such reduction was ascribed to the lower density of recycled PET compared with sand and to the poor adhesion between the recycled PET and matrix.

3. The decrease in ultrasonic pulse velocity values varied along with the proportions of sand replaced with recycled PET. PET-20 demonstrated the maximum reduction in UPV value (22%) compared with the reference sample.

4. Increasing the proportion of recycled PET reduced the compressive strength of the mortar. Compared with the PET-0 reference sample, the compressive strength of the PET-5, PET-10, PET-15 and PET-20 samples decreased by 11%, 16%, 20% and 27%, respectively, after 28 days of curing. Such reduction was mainly attributed to the low cohesion between the texture and the recycled PET, which acts as a barrier that prevents the cement paste from adhering to the natural sands.

5. Thermal conductivity, specific heat and thermal diffusivity are the most important thermal properties of a mortar. Replacing 20% of sand with recycled PET decreased thermal conductivity by 47% and specific heat by 39% and increased thermal diffusivity by 13%. The thermal behaviour of the mortar is directly related to its composition. Meanwhile, the lower thermal conductivity of the inclusions that replace the conventional components corresponds to a greater insulation efficiency. These improvements in thermal properties were ascribed to the recycled PET that limits heat flow. Another factor that explains the reduction in thermal conductivity is the increase in the number of voids, which subsequently increases the amount of trapped air. The ability of materials to store heat is determined by their specific heat capacity, whereas thermal diffusivity characterises the heat transfer abilities of materials. An eco-friendly mortar containing recycled PET is a less conductive mortar that does not allow heat storage.
In sum, recycled PET can be used to produce environmentally friendly mortar at certain replacement rates. This approach conserves natural resources such as sand and can effectively reduce the thermal conductivity of mortars. Therefore, mortars containing recycled PET have great potential for use as energy-efficient and eco-friendly building materials.

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Competing interests
The authors declare that they have no competing interests.

Author contributions
Nacer Akkouri: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, and Writing - Original Draft, Writing - Review & Editing. Oumaima Bourzik: Methodology, Writing - Review & Editing. Khadija Baba: Supervision, Resources, Writing - Review & Editing. Bassam A. Tayeh: Resources, Writing - Review & Editing.

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