Journal of Al-Azhar University Engineering Sector

Vol. 20, No. 77, October 2025, 1249-1269

UTILIZATION OF WASTE POWDER COATING AS A SUSTAINABLE ADDITIVE FOR IMPROVING MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE

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Citation:

S. G. Madbouly, A.Elshami, H. Khalil, M. F. Bakr," Utilization of Waste Powder Coating as A Sustainable Additive for Improving Mechanical and Durability Properties of Concrete", Journal of Al-Azhar University Engineering Sector, vol. 20(77), pp. 1249-1269, 2025.

Received: 30 April 2025

Revised: 20 June 2025

Accepted: 07 July 2025

Doi: 10.21608/auej.2025.380338.1829

ABSTRACT

By 2025, the global powder coating market is projected to produce 4.35 million tons annually, with nearly 0.42 million tons becoming waste (~9.6%). Recycling waste powder coating (WPC) could help address this issue while supporting sustainability goals. Lightweight concrete reduces cement use by 20% by incorporating waste materials, yet its production still contributes to 8% of global CO_2 emissions. This study examines the effects of adding WPC (0–30 %wt) on the mechanical properties of concrete and mortar under water and heat curing. Results show that, among the used WPC concentrations, 10% WPC enhanced 28-day compressive strength by 57% (heat-cured concrete) and 19% (water-cured), while mortar strength increases by 27% and 12%, respectively. Heat curing melts the polymer, sealing surface pores and improving strength. Brazilian tensile strength also rises significantly (82% for heat-cured concrete) using 10% WPC. FT-IR analysis confirms WPC's positive impact on hydration. The findings suggest WPC up to 10% can enhance concrete performance while reducing environmental impact.

KEYWORDS: sustainable concrete, High strength concrete, waste of powder coating (WPC), compressive strength, Brazilian tensile strength

استخدام مسحوق الدهان المهدر كمادة مضافة مستدامة لتحسين الخواص الميكانيكية والمتانة في الخرسانة

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الملخص

بحلول عام ٢٠٢٥، من المتوقع أن ينتج سوق طلاء المسحوق العالمي ٤,٣٥ مليون طن سنويًا، مع نفايات سنوية تقترب من ٠,٤٢ مليون طن (حوالي ٩,٦٪ من الإنتاج). لذلك، .(يمكن أن يساعد إعادة تدوير طلاء مسحوق النفايات (WPC) في معالجة هذه المشكلة مع دعم أهداف الاستدامة .تقلل الخرسانة

خفيفة الوزن من استخدام الأسمنت بنسبة ٢٠٪ من خلال دمج مواد النفايات، ومع ذلك لا يزال إنتاجها يساهم بنسبة ٨٪ من انبعاثات ثاني أكسيد الكربون العالمية .تبحث هذه الدراسة في آثار إضافة WPC (٠-٣٠٪ وزنيًا) على الخصائص الميكانيكية للخرسانة والملاط تحت الماء والمعالجة الحرارية .تُظهر النتائج أنه من بين تركيزات WPC المستخدمة، عززت نسبة ١٠٪ من WPC قوة الضغط لمدة ٢٨ يومًا بنسبة ٥٧٪ (الخرسانة المعالجة بالحرارة) و ١٩٪ (المعالجة بالماء)، بينما زادت قوة الملاط بنسبة ٢٧٪ و ١٢٪ على التوالي .يذيب المعالجة الحرارية البوليمر، مما يغلق مسام السطح ويحسن القوة . كما ترتفع قوة الشد البرازيلية بشكل ملحوظ (٨٢٪ للخرسانة المعالجة بالحرارة) باستخدام ١٠ .WPC %يؤكد تحليل FT-IR التأثير الإيجابي لـ WPC على الترطيب .تشير النتائج إلى أن نسبة WPC التي تصل إلى ١٠٪ يمكنها تحسين أداء الخرسانة مع تقليل التأثير البيئي.
الكلمات المفتاحية : الخرسانة المستدامة، الخرسانة عالية القوة، نفايات طلاء المسحوق(WPC) ، قوة الضغط، قوة الشد البرازيلية.

1. INTRODUCTION

Conventional concrete is the foundation of the quickly growing construction sector to fulfill global infrastructure requirements. Ultimately, this is reinforcing because research indicates it can reduce cement by approximately 20% and make it inexpensive and obtainable from materials that are byproducts of dust, marble and plastic waste. The environmental effect of concrete results from its production process, which involves the extraction of billions of tons of natural resources, including raw materials for cement and aggregates. This extraction leads to resource depletion and habitat effects, which present major ecological challenges. Aggregates, for example, can modify the landscape through mining operations and reduce biodiversity [1]. Because cement production, the key ingredient component of concrete, is a significant source of carbon dioxide emissions. In cement production, the calcination process liberates CO_2 when combined with energy-intensive production methods, it significantly related to climate change. Estimates suggest that cement production is responsible for about 8% of global CO_2 emissions, indicating its environmental footprint.

Normal concrete has a 28-day curing duration to form the required strength and durability [2]. For performance and durability, proper curing is very significant. Moreover, this is further aggravated in the case of high-strength concrete (HSC), which is used in vertical constructions. HSC has a higher cement content with a low water to cement ratio, which leads to increased evaporation and the bleed water is so scarce to fill the holes [3]. This ratio leads to faster execution in terms of increased early strength, but it may also lead to challenges, such as the need for more frequent removal of formwork, which can threaten the long-term integrity of the structure. These challenges highlight the need for innovative solutions to make the production process of concrete more sustainable and resilient.

To address the previous issues, the construction industry has turned to sustainable and innovative approaches. Recently, recycling waste and industrial byproducts has gained traction, leading to the development of green concrete. This eco-friendly variant uses material like fly ash (from coal burning) [4–6], blast furnace slag (from iron production) [7–9], and silica fume are also being explored, further decreasing reliance on natural resources and supporting sustainable development [10–12]. For instance, El-Sayed et.al [13] substituted cement with recycled glass powder (GP) and lime powder (LP) in ultra-high-performance self-compacting concrete (UHPSCC) and used mercury intrusion porosimetry (MIP), XRD, and 29Si MAS NMR to analyze microstructure, then tested followability and compressive strength up to 220 MPa. They found that, GP accelerated clinker dissolution, forming denser calcium silicate hydrate (C–S–H) which boosted compressive strength by >30 MPa and allowed 100% replacement of quartz powder/silica fume. In addition, combining GP and silica fume increased strength by 40 MPa due to synergistic reactions. The LP improved followability but required optimization to avoid excessive expansion. Other works such as [14] replaced cement with 5%, 10%, 15%, and 20% of rice husk ash (RHA), rice straw ash, or wheat straw ash and conducted X-ray diffraction and chemical analysis to verify pozzolanic reactivity. Then, they measured slump (workability), density, pulse velocity, sorptivity, compressive strength, and tensile strength. The authors found that the workability was decreased as ash content increased (higher ash = stiffer mix) and the compressive strength improved at ≤15% replacement, with optimal performance at 10% RHA. The main findings indicated that Ash-enhanced mixes showed lower sorptivity (improved water resistance) and higher density than plain concrete. These materials are combined with cement to create resource-efficient structures. Green concrete is characterized by its use of methods that do not emit carbon dioxide, lowering energy consumption while enhancing strength and durability.

Another potentially useful option is self-curing concrete, which eliminates the need for any form of external curing. This is particularly advantageous in regions where water is scarce or when curing is impracticable [15]. It relies on lightweight aggregates and chemical agents, such as water-soluble polymers, to provide some internal moisture for the continuous hydration of the cement [16]. This method has grown to become from laboratory research to practical field applications. This is expected to increase as the demand for high-performance concrete increases. There are various methods to add internal curing water into concrete mixtures. The internal curing water is in a way that it enhances freeze-thaw resistance and minimizes autogenous shrinkage [17]. It is interesting to see how advancements have improved the concrete that used to be considered less environmentally friendly.

Nevertheless, there is a call for more research to be done to improve the development of sustainable concrete formulations. An interesting investigation looks into the waste powder coating (WPC) as a self-healing agent in lightweight concrete. WPC is a by-product of the finishing process in the industrial coating industry that consists of the leftover powder that is dry finishing finishes of the industry as a substitute for liquid paint. It has encapsulated pigments that are polymer-encapsulated pigments that can be used to enhance the properties of the concrete and incorporate the self-healing mechanism. Therefore, lightweight concrete, which has a density ranging from 90-115 lb/ft^3 (1440-1840 kg/m^3) as compared to the normal density concrete that ranges from 140-150 lb/ft^3 (2240-2400 kg/m^3), is made by substituting in lightweight coarse aggregates such as expanded shale, clay, or slate.

It is ideal for applications requiring reduced weight, such as high-rise buildings and bridges, but its performance can benefit from improvements such as self-healing capabilities [2]. Lately, the knowledge of WPC role in lightweight concrete has posed great limitations, especially in terms of compatibility, optimal dosage, mechanical properties, and self-healing capabilities, which hinders the application of WPC in enhancing the sustainability and durability of concrete.

Though conventional concrete as well as some other green alternative concretes (with fly ash, slag, glass powder, agricultural ashes, etc.) have been extensively studied with regard to their mechanical characteristics and environmental performance, waste powder coating (WPC) incorporation is comparatively less explored due to a lack of systematic studies that explore the compatibility of WPC with lightweight concrete material, optimum dosage, and influence on mechanical characteristics and self-healing characteristics. In addition, few studies directly compare the strength, durability, and sustainability performance of WPC-modified concretes with conventional and alternative concretes. Furthermore, the self-healing mechanism provided by WPC, namely the interaction of polymer-encapsulated pigments within the concrete matrix, is not well understood or measured in the literature. Therefore, the advantages of using WPC in concrete especially in lightweight stems are: WPC is an industrial byproduct, and its use in concrete directs massive waste from landfills, promoting circular economy practices and environmental cost savings; WPC conserves natural resources and reduces virgin material use by partially replacing cement or other concrete components, similar to the benefit seen with other recycled admixtures; the polymer-encapsulated pigments in WPC can enhance self-healing properties of the concrete, extending durability and reducing maintenance needs a property not typical of most substitute binders; and finally, WPC's inherent water, rot, and chemical attack resistance can extend the service life of concrete structures, further encouraging sustainability.

In this work, we will perform the following tasks: evaluate suitability of WPC in lightweight concrete by investigating the compatibility of WPC with lightweight concrete constituents; measure the strength properties by taking point loads and tensile tests on the lightweight concrete on the incorporation of WPC; compare the performance with the conventional concrete by examining the strength, durability, and sustainability of the WPC incorporated lightweight concrete.

These goals seek to help generate empirical data on possible WPC applications, contributing to the development of unconventional concrete mixtures that solve the problems arising in the traditional industry. The environmental advantages of WPC implementation are unquestionable, as it allows for the elimination of industrial waste, reducing the volume of landfill waste and the amount of CO_2 generated due to the process of making concrete. These goals correspond to the strategies of reducing CO_2 emissions and establishing the principles of a circular economy in the construction industry.

2. EXPERIMENTAL

2.1. Materials

The properties of different materials that are used in this investigation can be described as follows:

The Bani-Sweif cement factory's ordinary Portland cement (CEM I 52.5 N) was utilized in this investigation. Cement underwent many laboratory tests following Egyptian Standards (ES 4756-1/2009) [18]. **Table 1** displays cement's mechanical and physical characteristics.

Table 1: The Cement's Mechanical and Physical Characteristics

Property		Result	Value limit
Specific gravity (g/cm^3)		3.15	-----
Specific surface area (cm^2/gm)		3600	≥2750
Setting time (Vicat apparatus) (min)	Initial	75	≥45 min
	Final	190	≤10 hours
Compressive strength 2 days (MPa)		23.5	≥20 MPa
Compressive strength 28 days (MPa)		54.4	≥52.5 MPa
Consistency of standard cement paste		W/C= 28 %	26% - 33%

All of the aggregates employed in this study, which included siliceous sand and dolomite, are readily available locally. To decrease the effect of aggregate's fine materials, coarse aggregates were cleaned three days prior to usage and allowed to dry.

Dolomite, a coarse aggregate with 10 mm of maximum nominal size, was brought from Ataka to Suez City. The coarse aggregate that was employed underwent testing in accordance with Egyptian Standards ES 1109-2008 [19]. The used aggregate's grading is displayed in **Table 2**, and **Table 3** lists the aggregate's physical characteristics.

Table 2: Grading of the Dolomite

Sieve size (mm)	37.5	20	10	5	2.36	1.18
Passing (%)	100	99.5	96	11.5	1.5	0.25

Table 3: Properties of the Dolomite

Property	Results	Value limit
Specific weight (gm/cm^3)	2.5	-
Bulk density (t/m^3)	1.36	-
Coefficient of abrasion (Loss Angloss) %	20	< 30
Coefficient of impact %	18	< 30
Crushing value %	29	< 30
Absorption %	1.8	< 2.5
Clay and fine dust content %	1	< 3.0

Natural siliceous sand was the fine aggregate employed in this study. A modulus of fineness of 2.9 is used for siliceous sand. The used sand was tested per Egyptian Standards ES 1109-2008 [19]. **Table 4** shows the characteristics of the siliceous sand.

Table 4: Characteristics of the Siliceous Sand.

Property	Results	Value limit
Specific weight (gm/cm^3)	2.3	-
Bulk density (t/m^3)	1.52	-
Fineness modulus	2.9	-
Material finer than No 200 sieve %	2.6	< 3%

The waste of powder coating (WPC) used in this research as a sustainable and high-strength material for concrete was brought from Colorama coatings factory in El-Obour City-Egypt. The composition of waste powder coating (WPC) is shown in **Table 5.**

Table 5: The Composition Of WPC.

Component	Weight % *
Polyester Resin	62
Hardener	3.263
Titanium dioxide	17
Flow control agent	1.300
Degassing agent	0.500
$BaSO_4$	15.937

* According to the manufacturer's data sheet.

Super plasticizer concrete admixture, Sikament, was delivered from Sika Egypt Company. This plasticizer was added a fixed percentage for all mixes (2% wt of the cement weight). **Table 6** shows the properties of the Sikament used in this work.

Table 6: Properties Of the Super Plasticizers.

Property	Result*
Base	Naphthalene Formaldehyde Sulphonate
Appearance / Color	Brown liquid
Density (at 20°C)	1.200 [20]

* According to the TDS.

Tap water was used for the mixture. To achieve high-strength concrete (HSC), the water/cement (W/C) for all beams was maintained at 0.35.

2.2. Methods

2.2.1. Characterization of WPC

The surface of the WPC sample was examined using a Scanning Electron Microscope (SEM) (Zeiss model EVO10) equipped with a Bruker EDX instrument (model quantax400) for elemental analysis. The samples underwent drying at 70°C, mounting onto holders with carbon tape, and sputter-coating with a thin gold layer to optimize imaging quality. SEM micrographs of the waste powder coatings (WPC) are shown in **Fig. 1a, b, c.** Elemental analysis and mapping of WPC particles were investigated by EDAX detector **Fig. 1 d, e.** These analyses have been performed at Military Technical College, Cairo, Egypt.

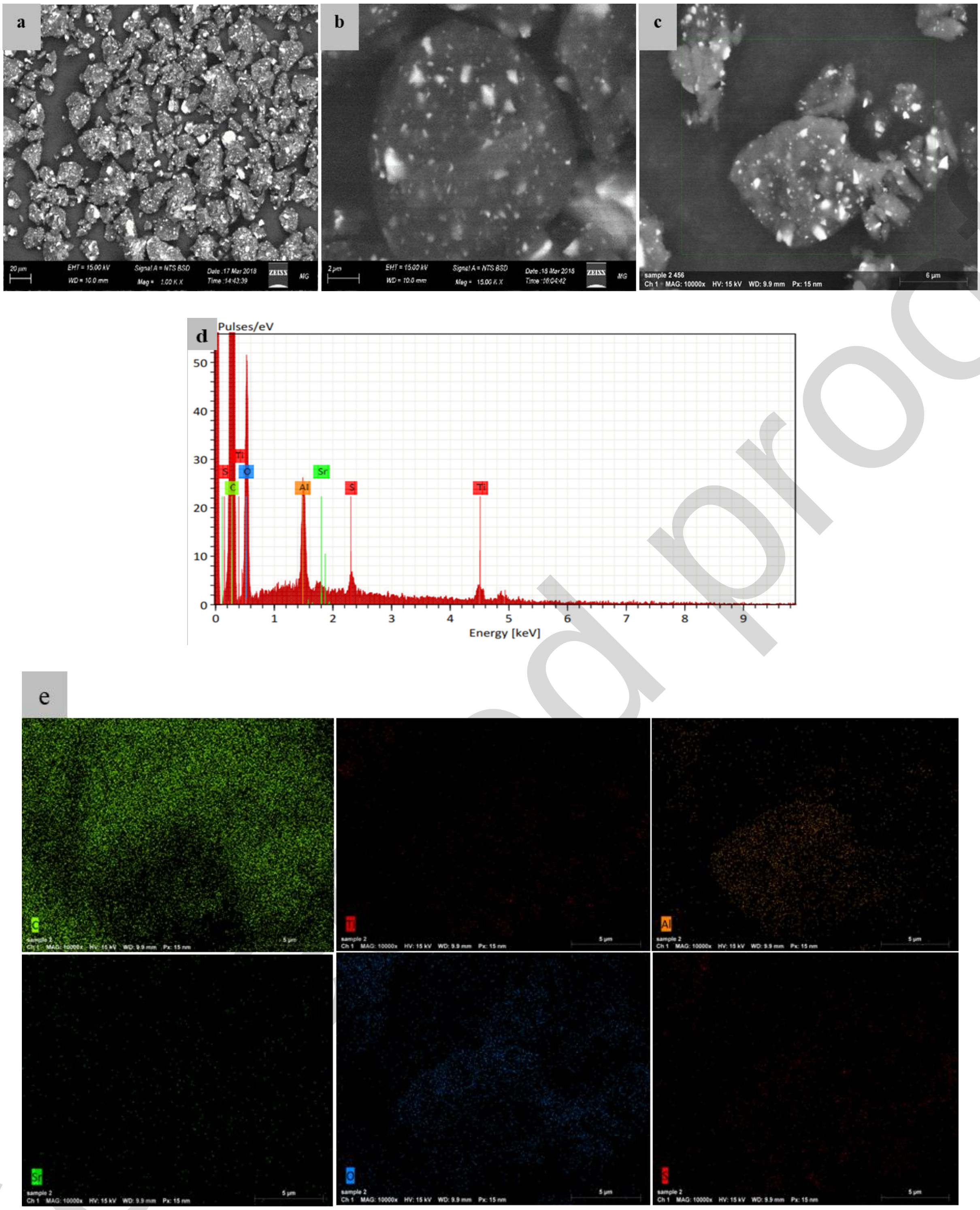

Fig. 1: SEM Image (a, b, c), Elemental Analysis (d), and Mapping (e) Of WPC, respectively.

2.2.2. Mix design

The weight of each component needed to make one cubic meter of concrete can be calculated using the absolute volume method, and the preliminary mix proportions were established in trial mixes. The concrete components' s governing Equation 1 is:

$$\frac{C}{\gamma_C} + \frac{S}{\gamma_S} + \frac{G}{\gamma_G} + \frac{WPC}{\gamma_{wpc}} + \frac{W}{\gamma_W} + \frac{Pz}{\gamma_{Pz}} = 1000 \text{ liter} \qquad (1)$$

Where:

C	Weight of cement (kg)	γ_C	specific gravity of cement
S	Weight of fine aggregates (kg)	γ_S	specific gravity of fine aggregates
G	Weight of coarse aggregates (kg)	γ_G	specific gravity of coarse aggregates
WPC	Weight of waste powder coating (kg)	γ_{wpc}	specific gravity of wpc
W	Weight of water (kg)	γ_W	specific gravity of water
Pz	Weight of superplasticizers (kg)	γ_{Pz}	specific gravity of superplasticizers

The required quantities of cement, coarse aggregates, fine aggregates, WPC, super plasticizers, pozzolanic admixtures and water for each mix were determined according to the mix design. The concrete mix proportions are given in **Table 7.** For testing the effectiveness of the used additives for the cementitious paints, the same trials without coarse aggregates in the mortar are given in **Table 8.**

Table 7: The Concrete Mix Proportions.

Mix	% WPC	Usage	Curing
C1 (Blank)	0	--	Water
C2	5	Addition	Water
C3	10	Addition	Water
C4	20	Addition	Water
C5	30	Addition	Water
C6 (Blank)	0	--	Heat
C7	5	Addition	Heat
C8	10	Addition	Heat
C9	20	Addition	Heat
C10	30	Addition	Heat

Table 8: The Mortar Mix Proportions.

Mix	% WPC	Usage	Curing
M1 (Blank)	0	--	Water
M2	5	Addition	Water
M3	10	Addition	Water
M4	20	Addition	Water
M5	30	Addition	Water
M6 (Blank)	0	--	Heat
M7	5	Addition	Heat
M8	10	Addition	Heat
M9	20	Addition	Heat
M10	30	Addition	Heat

2.2.3. Test specimens

Processing the molds of wooden cubes and plastic cylinders and coating them internally with oil to facilitate the process. Wooden Cube molds 10×10×10 cm and plastic cylinder molds 10 x 20 cm were used for the preparation of concrete specimens are presented in **Fig.2**.

Fig. 2: Cube and Plastic Molds.

2.2.4. Mixing

Using a horizontal mixer, the components of the concrete were mixed. In a dry state, the cement, WPC, pozzolanic admixtures, and coarse and fine aggregates were introduced to the mixer and mixed for two minutes as shown in **Fig. 3**, Practical experiments should be used to determine the required mixing time. To achieve homogeneity and uniformity, superplasticizer and mixing water were added progressively and combined for an additional two to three minutes. Every concrete and mortar mix were mixed according to the same procedure.

Fig. 3: Mixer Used in Research.

2.2.5. Casting

Without any attempt to vibrate, the freshly mixed concrete or mortar was put into the molds under its own weight. After the molds were filled with concrete as show in **Fig. 4**, the specimens were kept in the molds for a whole day in the air.

Fig. 4: Fresh Concrete in Molds.

2.2.6 Curing

Before the test, the specimens were taken out of the molds and kept in fresh water. The specimens were taken out of the molds and heated to 160 °C for three hours to cure them in **Fig. 5**. The specimens were then allowed to cool for two hours before being treated with fresh tap water in preparation for the tests. As illustrated in **Fig. 6**, it is observed that the WPC polymer melts and seals the pores and gaps on the cube surface after the samples are removed from the oven after curing.

Fig. 5: Heat and Water Curing of Specimens.

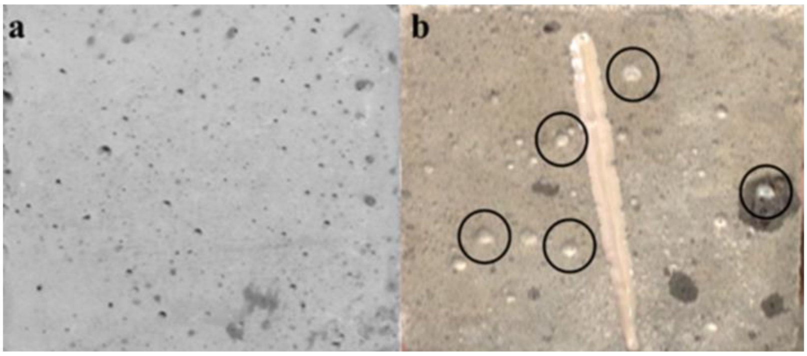

Fig. 6: Surface Pores of Concrete (a) Without and (b) with WPC After Heat Curing

2.2.7. Testing of hardened concrete

2.2.7.1 Compressive strength test

One of the most notable characteristics of hardened concrete is its compressive strength, which is also regarded as the defining material value for concrete categorization. Cubic specimens of 100 x 100 x 100 mm were made to assess the compressive strength at 7, 14, and 28 days following the casting. Before being tested, all of the concrete cube specimens were taken out of the curing tank and allowed to dry in the lab for roughly two hours. Each mixture was tested on three specimens at each testing age, and the average was calculated. In the concrete laboratory of Mansoura University's college of engineering in **Fig. 7**, a hydraulic testing machine with a 200-ton capacity and a 0.5-ton precision was used to perform the compressive strength test. The following formula was used to determine the compressive strength (Fc):

$$\mathbf{Fc} = \frac{\mathbf{Pc}}{\mathbf{A}} \qquad (2)$$

Where:
Pc is the maximum load in compression.

A is the cross-section area of the specimen (100x100) mm.

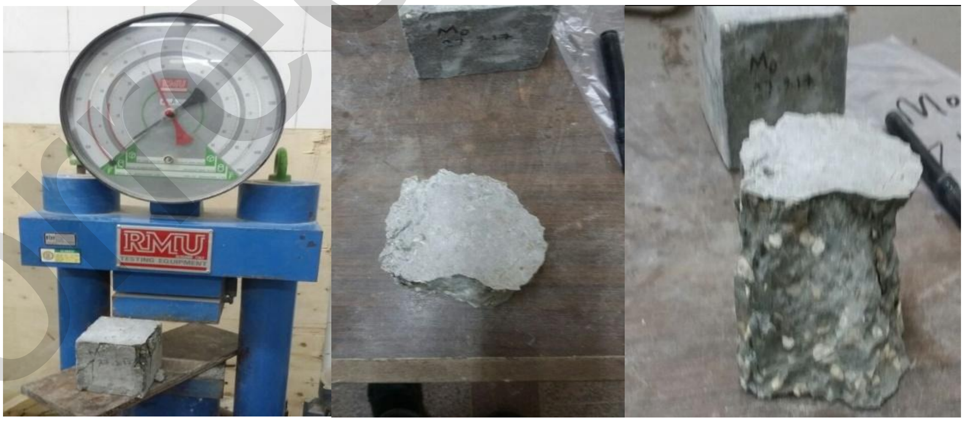

Fig. 7: Hydraulic Testing Machine Used in Compressive Strength Test.

2.2.7.2 Brazilian tensile strength

In the Brazilian test, two diametrically opposed generators are used to apply a consistent stress along a line, compressing the diameter of a cylindrical specimen until failure is achieved. Due to its simplicity and affordability, this experimental method is frequently used to measure the tensile strength of concrete. It can be applied to cylindrical specimens (Both molded and hardened concrete cores) as well as cubic or prismatic ones, and it has been outlined in several guidelines and recommendations, including UNE-EN 12390-6 [21], ASTM C-496 [22], and CPC6 [23]. A crucial factor in hydraulic fracturing, tensile strength forecasts the start and spread of fractures in concrete.

The cylinders of conventional dimensions (10 x 20 cm) were ready for tensile strength testing 28 days following casting as shown in **Fig. 8.**

Fig. 8: Brazilian Tensile Strength Testing.

2.2.8. Chemical composition

The infrared spectra (wavenumber 500 to 4000 cm^{-1}) were recorded at 4 cm^{-1} resolution using an FTIR spectrometer Nicolet Nexus 8700, ThermoFisher Scientific, USA, by collecting 64 scans.

2. 3. RESULTS AND DISCUSSION

3.1. Analysis of WPC

The composition of the WPC **Table 5** shows a polyester resin-based system heavily modified with inorganic fillers and additives. Polyester resin, constituting 62% of the matrix, has the function of matrix binder, which provides mechanical strength and chemical resistance. This was the conventional role of the polyester in the composite materials [24]. The hardener (3.263%) helps in the cross-linking reaction during the hardening process, which is a very important step in achieving thermoset properties. The low percentage of the hardeners is a typical value for peroxide-type hardeners, which allow efficient polymerization without the degradation of the matrix structure [25,26].

Significantly, titanium dioxide (TiO_2), 17%, performs the dual function of whitening agent and functional filler. Moreover, the latest research on the efficiency of TiO_2 as a means to enhance the UV and photocatalytic advantage of the composites and improve the durability of the composites for outdoor applications [27,28]. Barium sulfate ($BaSO_4$)(15.937%) is a part of inorganic fillers and was added to the formulation to regulate the density of composites or to enhance the resistance to radiation, which is a positive effect used in industrial composites [29]. The addition of rheology modifier (1.3%) and degassing agents (0.5%) can be explained by the necessity of stabilizing the viscosity and preventing the formation of voids that hinder the process of the uniform distribution of fillers in the matrix.

The SEM photo **Fig. 1 a, b, c**, and the analysis of the elemental distribution **Fig. 1e** can be considered as proof of the uniform distribution of TiO_2 and $BaSO_4$ particles, which is extremely important for obtaining the required mechanical properties. The elemental analysis, **Fig. 1d,** will show the presence of the following elements: Ti, Ba, S, and C, which is fully compatible with the data presented in **Table 5.**

3.2. Effect of WPC Addition on the Concrete and Mortar Compressive Strength at Different Curing Methods

Fig. 9a, b shows the relationship between age (days) and Fcu (kg/cm^2) of the concrete with the addition of WPC at 0, 10, 20, and 30 % under water and heat curing conditions, respectively.

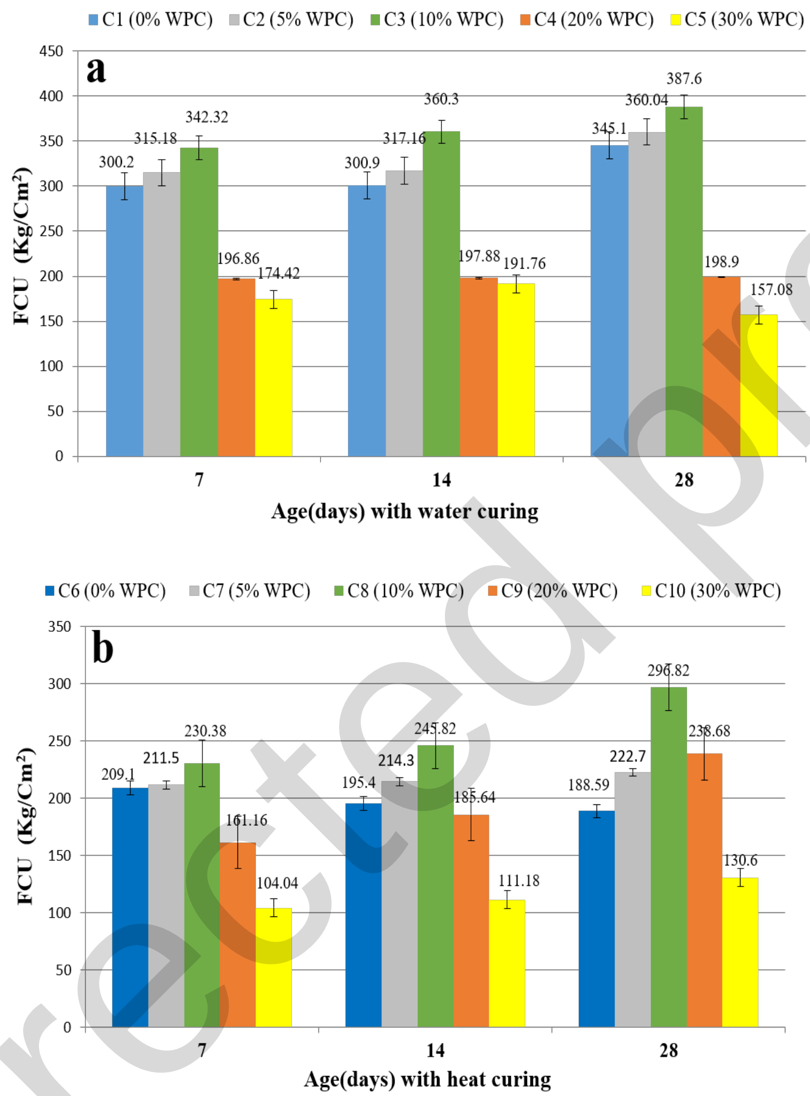

Fig. 9: Relationship Between Age (Days) And Fcu (Kg/Cm^2) of Concrete Contains Different Concentrations of WPC Using (a) Water Curing, and Heat Curing (b), respectively.

Notably, the maximum compressive strength was achieved with the addition of 10% WPC in both conditions (from 345.1 and 188.59 kg/cm^2 (0% WPC) to 387.6 and 296.82 kg/cm^2 (10% WPC) at 28 days under water and heat curing, respectively). This suggests that WPC enhances the concrete's strength up to a certain point, beyond which additional WPC (e.g., 20% or 30%; 198.9, 157.08 kg/cm^2, and 238.68, 130.6 kg/cm^2, respectively) may not yield further improvements or could even reduce the effectiveness. This behavior is typical in concrete mix design studies involving additives. Additives like polymers or fibers often improve mechanical properties by enhancing bonding within the cement matrix or reducing porosity. However, an optimal concentration exists due to factors such as workability, dispersion, or potential interference with hydration processes at higher concentrations. The finding that 10% WPC provides the peak strength aligns with such principles, indicating an optimal balance between additive benefits and concrete matrix compatibility under water curing conditions. The results align with research on concrete additives aimed at improving mechanical properties. For instance, studies on polymer-modified concrete (PMC) often report enhanced compressive strength with optimal polymer content, similar to the 10% WPC peak observed here. A reference [30] discusses how additives can improve strength by filling voids or enhancing bonding, though excessive amounts may disrupt the mix. Similarly, it was noted that heat curing accelerated the strength gain of concrete, which could interact uniquely with additives like WPC [31].

Using water and heat curing, **Fig. 10 a, b** illustrates the relationship between age (days) and Fcu (kg/cm^2) with 0, 5, 10, 20, and 30% (WPC) in the mortar.

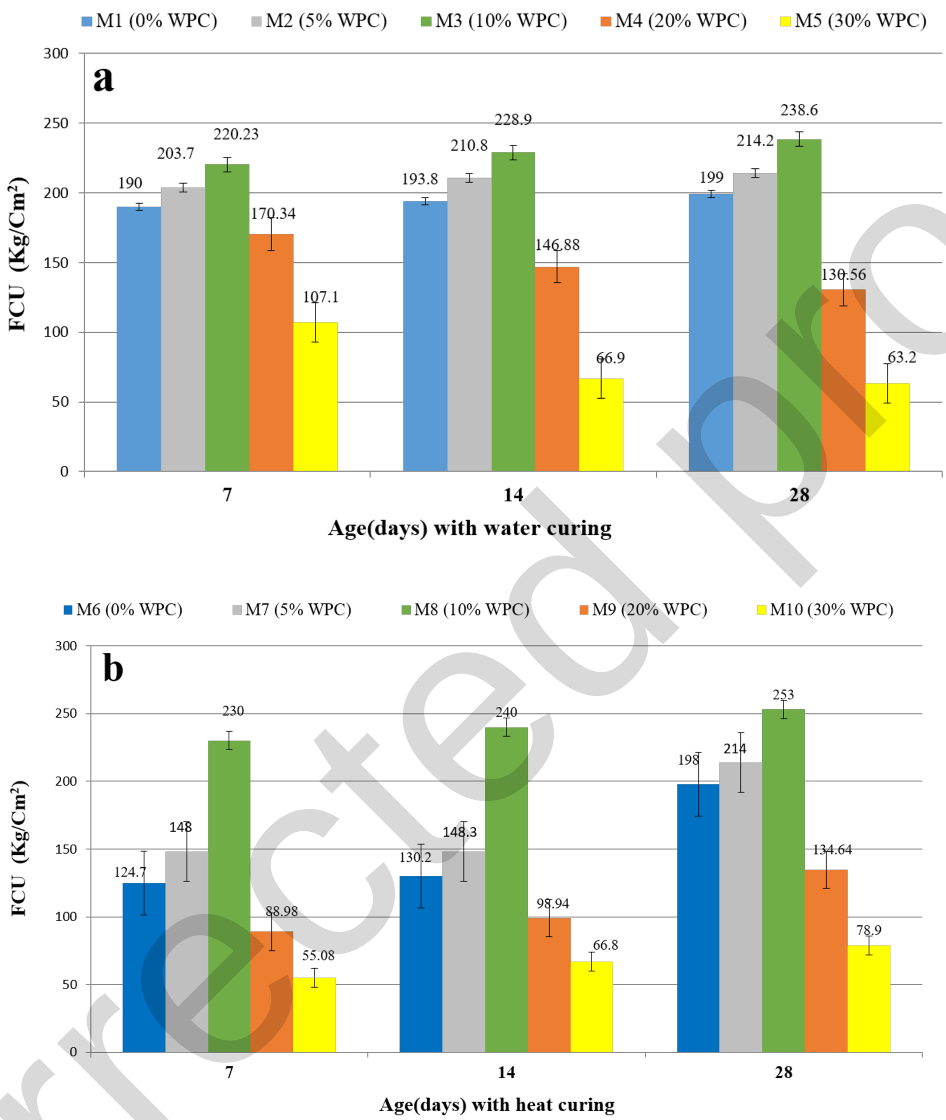

Fig. 10: Relationship Between Age (Days) and Fcu (Kg/Cm2) of Mortar Containing Different Concentrations of WPC Using (a) Water Curing, and Heat Curing (b), Respectively.

At 7, 14, and 28 days, it was shown that the compressive strength increased, reaching its highest value using 10% (WPC) in both water and heat curing conditions (from 199 (0% WPC) to 238.6 (10% WPC) at 28 days under water curing, and from 198 (0% WPC) to 253 (10% WPC) at 28 days under heat curing, respectively). In general, the compressive strength values obtained from heat-cured samples were superior to those obtained from water-cured samples. This might be because heat causes the polymers that are a part of WPC to crosslink and enhance the strength using WPC up to 10% and beyond this, the strength was decreased may be as a result of increased crosslinking, which affects the hydration reaction of cement [32–34].

3.3. Brazilian tensile strength after 28 days for concrete.

The relation between the WPC Ratio (%) and Fcu (kg/cm^2) at 28 days under water and heat curing of concrete is depicted in **Fig. 11** a, b, respectively. When cured in water, the tensile strength was found to increase steadily with increasing WPC addition. Specifically, the tensile strength was increased by approximately 9% when the percentage of WPC content was raised from 0% to 5%, and then became significantly higher by 25% as the content of WPC was increased from 5% to 10%.

This kind of trend suggests that up to 10% WPC addition maximizes tensile strength in concrete. The improvement in tensile strength is attributed to the enhanced hydration process induced by the WPC, which would more effectively strengthen the microstructure and interfacial bonding of the cement matrix [30]. Moreover, the influence of WPC under heat-curing conditions was more prominent for tensile strength. Tensile strength increased by 42% as WPC content increased from 0% to 5%, by another 30% from 5% to 10%. Tensile strength reduced beyond 10% WPC content, exhibiting a peak 10% WPC content for maximum tensile strength in heat curing. Heat curing enhances accelerated hydration reaction, leads to more dense microstructures and improved mechanical properties, which is the cause for increased percentage gains in comparison to water curing [35].

Below 10% WPC, reduction could be due to particle agglomeration due to excessive powder content or insufficient water for complete hydration. Overall, the highest tensile strength was observed at 10% WPC in both curing conditions, and heat curing showed greater improvement in tensile strength. The findings agree with past studies that indicate the correct proportion of additive content enhances tensile strength through optimizing pore structure and interfacial transition zones (ITZ) of concrete [36].

The Brazilian tensile strength test has been extensively known to possess good reliability in measuring tensile properties, which are very critical in concrete performance under service loads [37]. **Table 9**, presents a brief comparison between the effect of WPC used in this study and other studied materials on the concrete performance. From the table, it was noted that, the WPC at around 10% replacement optimally enhances compressive and tensile strength of mortar and concrete, with water curing enhancing ultimate strength.

This is consistent with trends in other waste additives like waste paper, polymer waste, and bottom ash from coal that enhance mechanical properties at low to intermediate amounts of replacement but degrade performance when exploited. WPC supports only self-healing light concrete and exhibits established chemical bonding with products of cement hydration. All these wastes help in sustainability via reduced landfill use and CO_2 emissions, promoting circular economy strategies for building.

Table 9. Summary of the Effect of Some Additive Wastes on the Concrete Performance

Aspect	Waste Powder Coating (WPC)	Other Waste Materials Used as Concrete Additives
Type of Waste	Waste powder coating from polyester resin industry	Coal bottom ash, waste plastic, fibers, wood ash, recycled concrete powder, waste paper, polymer waste mix, etc. [38–42].
Optimal Replacement %	10% WPC optimal for strength enhancement	Typically 5–15% for many wastes; e.g., 5–10% for waste paper, 7% for polymer waste mix, 12–15% for waste paint. [38–41].
Effect on Compressive Strength	Increased from 345.1 to 387.6 kg/cm² (water curing) at 10% WPC; significant drop beyond 10%	Improvements reported, e.g., polymer waste mix increased strength by ~10-13%, waste paper concrete improved strength at 5-10%, coal bottom ash and fibers enhance strength variably [38–41].
Effect on Tensile Strength	Tensile strength improved by 25-30% at 5-10% WPC	Waste plastic fibers and other additives generally improve tensile and flexural strength due to fiber reinforcement [43].
Curing Method Impact	Water curing yielded higher ultimate strength than heat curing for concrete; heat curing accelerated strength gain in mortar	Some wastes benefit from thermal or chemical activation to improve reactivity (e.g., recycled powder from concrete waste)[42]
Chemical Interaction	FT-IR confirmed chemical bonding between WPC polymers and cement hydration products	Polymer wastes and some mineral wastes chemically interact with cement matrix improving bonding and hydration [40,44]
Environmental Benefits	Utilizes industrial polyester resin waste, reduces landfill and CO_2 emissions, supports circular economy	Reduces landfill, lowers natural resource use, decreases CO_2 emissions, promotes sustainability [38–42].
Limitations	Strength drops significantly beyond 10% WPC addition	High replacement levels (>15-20%) often reduce strength and durability; variability depends on waste type and treatment [38,39,41,42].
Additional Properties	Self-healing and light concrete production possible	Improvements in durability, water absorption, slump flow, and impact resistance reported depending on waste type [40,41,44]

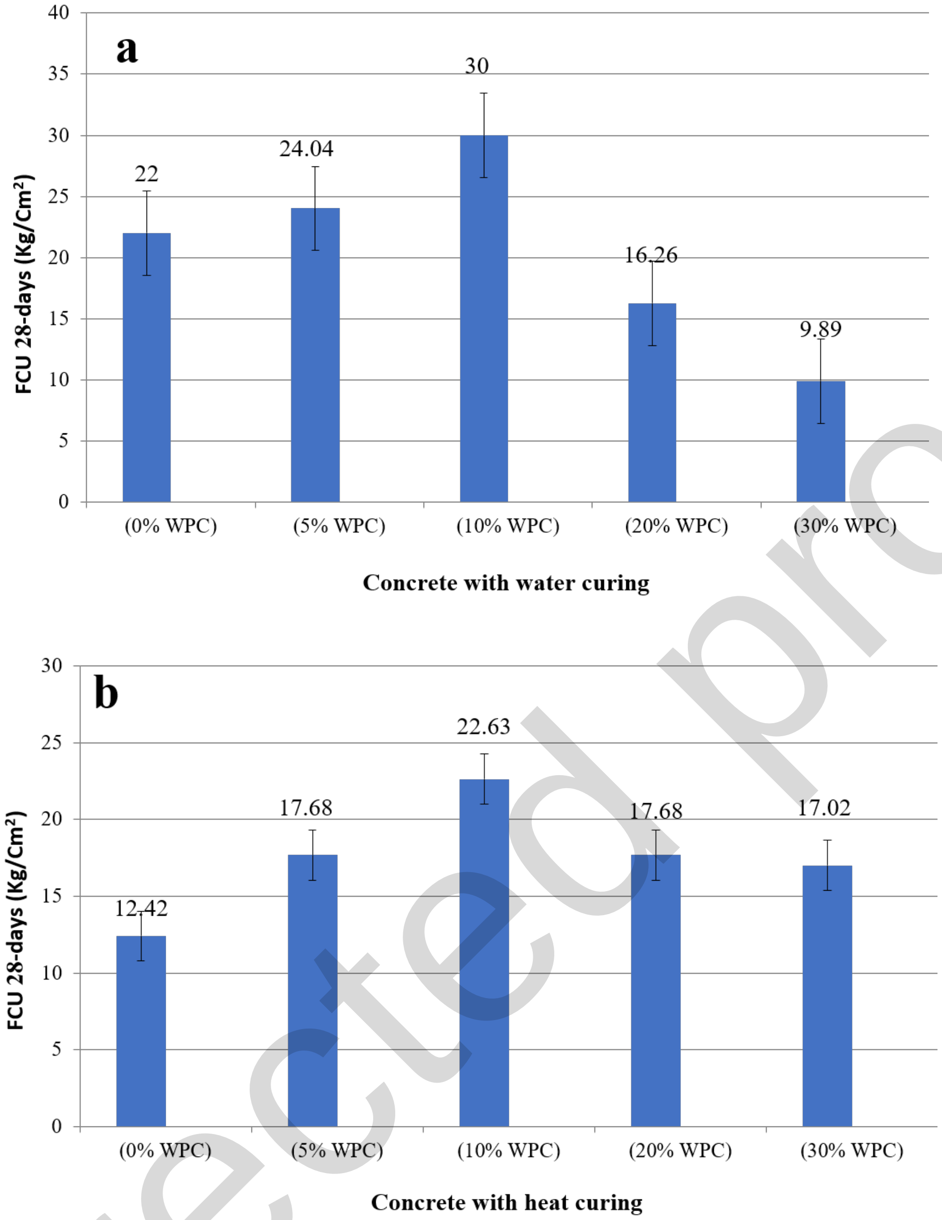

Fig. 11: Relationship Between WPC Ratio (%) and Fcu (Kg/Cm2) of Concrete at 28 Days (a) Water, and (b) Heat Curing Conditions, Respectively.

3.4. FT-IR Analysis

Fig. 12 displays the FT-IR results for the neat and modified mortar with WPC. By examining the functional groups of cement mortar and the polyester-modified mortar, respectively, the FTIR result illustrates the impact of the additives on the hydration process and cement mortar products. The broad peak at 3400–3700 cm^{-1} is ascribed to –OH groups in the polymer-modified composite and cement mortar, which most likely came from water molecules or chemicals in the concrete mixture that contained hydroxyl [43,45,46]. The absorption peak at approximately 3642 cm^{-1} is attributed to the stretching vibrations of the –OH group in portlandite (calcium hydroxide, $Ca(OH)_2$), which is a product of cement hydration [45]. However, the broadband at about 3450 cm^{-1} was caused by either the adsorbed water molecules on the cement's surface [47] or the -OH group from the tiny quantity of water that was still present in other hydration products [48]. More C species were discovered during the hydration process, as indicated by the small, broad peak at about 2980 cm^{-1} that belongs to the C-H in the modified mortar. The peak at 2880 cm^{-1}, which shows the presence of C-H symmetric stretching of the methylene (CH_2 and CH_3) groups in the modified mortar

[43,49], suggests the addition of WPC to the mortar. Out-of-plane bending vibration in the SO_4 group ($BaSO_4$) is the cause of the little peak at about 633 cm^{-1} [50]. The peak at about 1723 cm^{-1} is attributed to C=O stretching in ester and carboxylic acid groups, while carbonyl stretching typically occurs between 1800 and 1600 cm^{-1} [43]. The cross linker's C-N in WPC is connected to the peak at about 1594 cm^{-1} [51]. The in-plane deformation bending vibration of Si-O is linked to the peaks at 481 and 523 cm^{-1} [52].

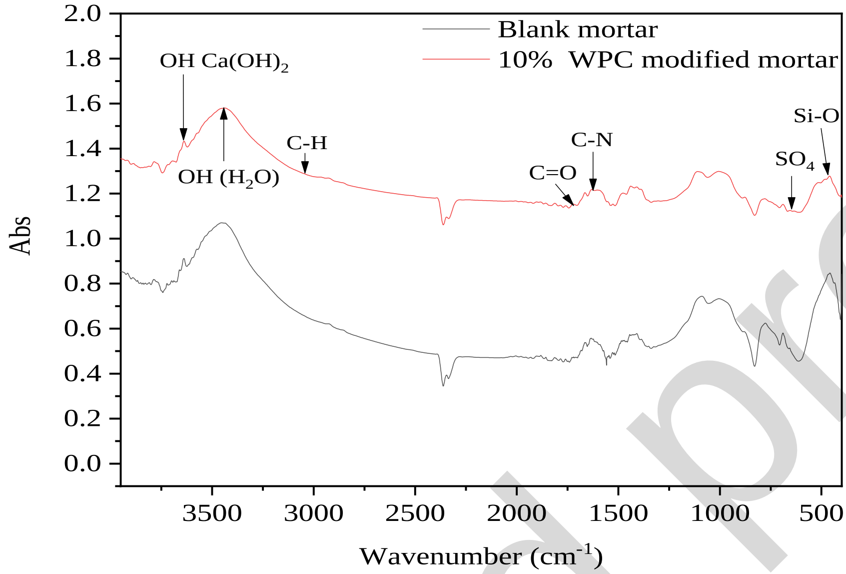

Fig. 12: FT-IR Spectra of Mortar With and Without WPC

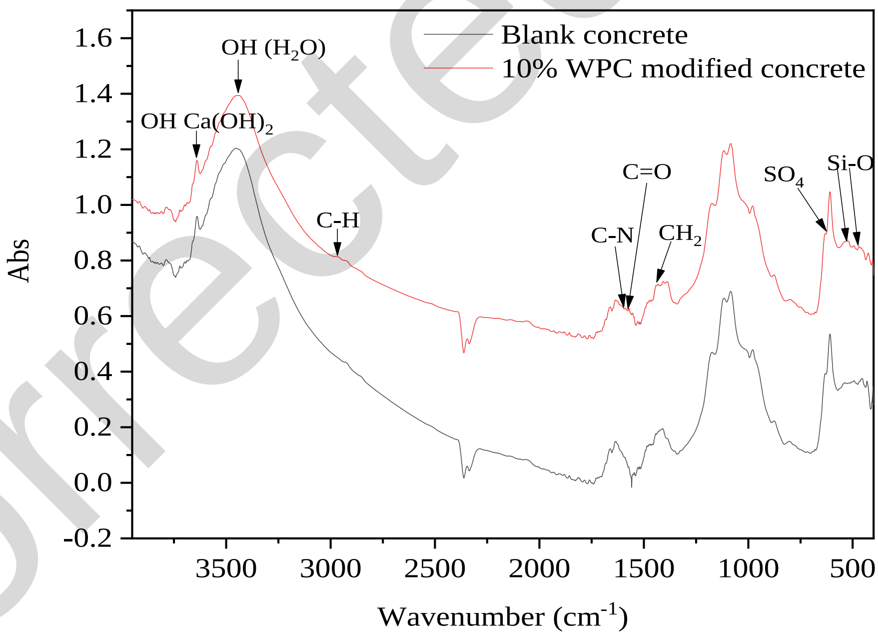

Fig. 13: FT-IR Spectra of the Concrete With and Without WPC

Fig. 13 shows the infrared spectra of the modified and blank concrete. The findings showed that the composite's C=O shrinking vibration band was located at about 1569 cm^{-1}, whereas the polyester's $–CH_2$ and $–CH_3$ stretching vibration may be represented by the band at about 2961 cm^{-1} [53]. The peak at around 1445 cm^{-1} is associated with the CH_2 and CH_3 groups, while the OH functional group for polyester appears wider at about 3442 cm^{-1} [54]. The bending vibration of Si-O is associated with the peaks at 468 and 529 cm^{-1} [54].

CONCLUSION

This study investigated the use of waste powder coating (WPC) and additives to produce green and self-healing light concrete. Based on the research findings, we can conclude that 10% WPC for enhancing compressive strength (from 345.1 to 387.6 kg/cm^2 (water curing) and 188.59 to 296.82 kg/cm^2 (heat curing), and from 199 to 238.6 kg/cm^2 (water curing) and 198 to 253 kg/cm^2 (heat curing) in the case of mortar). The tensile strength of the concrete under water curing has gained 25% improvement by increasing WPC from 5–10%. Under heat curing, tensile strength increased by 30% at 5–10% WPC. Furthermore, reduction in the performance beyond 10% WPC was observed (compressive strength plummeted significantly at 20–30% WPC (concrete fell to 198.9 kg/cm^2 (20%) and 157.08 kg/cm^2 (30%) under water curing, while the mortar also went through a similar decline). In addition, heat curing has hastened the development of strength in mortar (10% WPC mortar attained 253 kg/cm^2 under heat curing versus 238.6 kg/cm^2 under water curing). Increased ultimate strength of concrete by water curing was also noted; 10% WPC concrete with a value of 387.6 kg/cm^2 (water curing) against 296.82 kg/cm^2 (heat curing). FT-IR verifies WPC incorporation properly by observation of C-H stretching peaks at 2961 cm^{-1} and C=O ester peaks at 1723 cm^{-1} for the modified mortar/concrete that guarantee chemical interaction between WPC polymers and hydration products of cement. Generally, WPC supports sustainability goals by utilizing industry waste (e.g., polyester resin), reducing landfill space and CO_2 emissions which supports circular economy practice within construction industries. However, the study's findings are limited to its specific materials, curing methods, and short-term testing. Future research must investigate long-term durability, economic feasibility, and validate these results with field trials and other waste materials.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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