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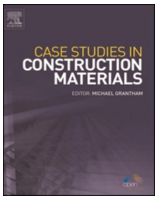

Experimental evaluation of using pyrolyzed carbon black derived from waste tires as additive towards sustainable concrete

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ABSTRACT

Waste tires (WTs) are one of the most critical environmental problems worldwide. Since the WTs cannot be landfilled or burned, innovative solutions and proper solid waste management are needed. Therefore, several methods have been proposed for WTs treatment. Among these methods, the pyrolysis process is considered the most favorable. Pyrolysis is a process of converting WTs in absence of oxygen into pyrogas, fuel oil, and a by-product, which is pyrolyzed carbon black (PCB). To introduce the idea of eco-friendly and sustainable concrete, it is proposed to use PCB as an additive in concrete structures. In this experimental investigation, PCB samples are obtained from a local pyrolyzed WTs plant. Several concrete properties are investigated considering different mixes of different weight percentage ratios of PCB to cement (PCB/c); 0% (control sample), 3%, 3.5%, 4%, 4.5%, 5%, 7%, and 10%. Typically, fixed amounts of cement, water, sand, aggregate, and superplasticizer are prepared following international preparation standards, and then, mixed with the aforementioned PCB/c ratios. Afterward, an array of mechanical tests are performed investigating properties enhancements. These tests are slump, compressive strength, and abrasion resistance, along with water absorption. Results show a noticeable increase in the compressive strength for tested samples of 29.3 and 38.4 MPa were obtained at a ratio of 4% for 7 and 28 days, respectively. This is combined with a slight reduction of slump results; however; slump values are still within standard limits for most of the mixes. In addition, abrasion resistance results suggest a vital improvement in the PCB/c mixes. Also, water absorption measurements reflect enhancement of concrete mixes up to a specific percentage of PCB. Amongst tested PCB/c ratios, the study highlights the optimal value to be between 3% and 5%. In addition, a multi-level framework on the impact of institutional pressures on the adoption of PCB as an additive to cement has been addressed to rationalize and raise awareness towards the applicability of such a feasible approach. Thus, the overall results reflect the promising horizons of using PCB as an improving additive material in concrete mixes.

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1. Introduction

Concrete has become a globally ubiquitous artificial construction material and is considered one of the most important materials in the construction industry [1]. The massive production of cement, which is a vital composite of concrete, creates serious problems for the environment due to the emission of CO_2 during its industrial production. Cement manufacturing accounts for approximately 5 – 6% of all CO_2 produced by human practices and around 4% of global warming [2]. The CO_2 and other particulate matters emissions are very harmful and create serious changes in the environment. Approximately, 1 kg of CO_2 is released into the atmosphere when 1 kg of ordinary cement is manufactured [3]. Also, the transportation industry has remarkably propagated in the last few decades [4]. This growth is reflected in the number of waste tires (WTs). WTs are a critical problem that is spreading worldwide, which is considered as one of the main problems behind different types of pollutions. In 2019, three billion tires were sold around the world which is expected to be accumulated illegally in the landfills [5,6]. The vast spreading of these two sectors, i.e., construction and transportation, creates a problem of solid waste management which has a negative environmental impact [7–11].

For the Palestinian context and for a time interval of 5 years (2014 – 2019), the Palestinians' population are increased by 12.3% which is reflected back in the construction industry sectors with an average annual increment of 0.7% in the issued building licenses [12,13]. On the other hand, in 2010, around 3044 tons of WTs are accumulated in the West Bank of the Palestinian territories [14]. However, for larger societies, the number of WTs is considered much greater than the aforementioned numbers.

Despite the new practices of minimizing the hazardous pollutants during the manufacturing of cement and burning WTs in the open atmosphere which was adopted by many researchers [8,9,15], still, there is a need for other alternatives which must be addressed immediately. Those alternatives must foster a waste-to-product approach to adhere to the rapidly increasing demand in the construction and transportation sectors. Hence, the used material must be environmentally friendly and more sustainable. Concrete, which is characterized as heterogeneous material, is made by mixing specific ratios of cement, water, and aggregates. Additionally, binding agents can be added to the mix to enhance the fresh and hardened concrete properties. Thus, the mixture progressively solidifies, creating a solid material whose strength varies according to its ingredients. However, the presence of pores in concrete is considered a major problem since ever concrete was discovered. These pores attract water that leads to serious undesirable effects such as reduced compressive strength, less abrasion resistance, more acid intrusion, freezing and thawing, and decreased resistance to chloride-ion [16]. Thereinto, various attempts have been reported in the open literature to incorporate different additives and/or waste materials in concrete mixture such as glass [17], plastics [17,18], wood biochar [9,19,20], mineral additives (SiO_2, zeolites) [21–25], fly ash [24, 26–28], alum sludge which is a water industry waste [29,30], recycled concrete aggregates [31], crumb rubber [32–37], carbon powder [38], pyrolyzed carbon black (PCB) [4], and carbon nanotube (CNT) [25,39].

The aforementioned materials have their pros and cons. For example, a series of earlier investigations have been conducted on the utilization of WTs as a crumb rubber in concrete and pavement [32–36, 40–43]. They indicated that the aggregation of crumb rubber would enhance to some extent the concrete characteristics namely; impact tup, inertial load, bending load, flexural impact, toughness, and deformation ability. Dong et al., [36] studied the behavior of rubberized concrete-filled steel tubes under combined loading. The investigations explicitly implied that the rubberized concrete specimens offered a notable increase in ductility and decrease in strength compared to that of the confined conventional concrete ones. They concluded that the high ductility of rubberized concrete led to a well bond between the concrete core and the steel tube and procured higher energy absorption compared to conventional ones. Though, mechanical and physical properties results of rubberized concrete revealed that property values are reduced and mainly dependent on the quantity and type of the mineral aggregates replaced [18,31,34,35] and the rubber size and concentration [34,44, 45].

Herein, the large-scale abundance of WTs globally emerges PCB, which is a by-product of the pyrolysis process, as an inevitably low-cost green additive of concrete, since around 75% of WTs are manufactured with carbon-based material [46]. Pyrolysis, also called thermolysis, is a process of chemically decomposing apart chemical bonds at elevated temperatures up to 600 °C at nonoxidative conditions [8]. While earlier efforts focus on finding new pyrolysis reaction pathways that work at lower temperatures and faster reaction rates using bulk and nanocatalysts [8,47,48]. Many scholars highlighted the benefit of utilizing PCB in different fields such as; steel corrosion [49], CO_2 sequestering [9], shielding concrete [38], replacement of cement and sand [33,43], replacement of both fine and coarse mineral aggregates [34,35], etc. For instance, Bompa et al., [34] utilized rubber derived from waste tires of cars, trucks, and buses as a potential sustainable replacement of both fine and coarse mineral aggregates. The influence of the replacement ratio of 60% of mineral aggregates using the rubberized aggregate with a particle size up to 10 mm was investigated. A comparison between conventional concrete and rubberized concrete mixes revealed that the mechanical properties were strongly influenced by the rubber replacement of the mineral aggregates. Moreover, Ali F. et al., [4] utilized PCB (particle size ranged between 0.15 and 0.075 mm) as a filler material in concrete by replacing fine aggregate with PCB at various percentages of weight (0, 25, 50, 75, and 100 wt%), considering constant water to cement (w/c) ratio of 0.65. These high percentages of replacement play a significant role in developing lightweight concrete. In addition, a compressive strength test was applied following the equivalent cube test mechanism. Their research findings following, the American Concrete Institute (ACI) standard [50], which assures that at 25% and 50% replacement, the lightweight concrete can sustain the strength of 18–20 MPa which can be used as structural concrete.

However, there is a lack of studies that explore the effect of adding PCB as a filler in the concrete. Therefore, the primary aim of this research is to examine different concrete mixes with PCB. This approach is believed to help the Palestinian community with the issue of WTs management and establish a concept of sustainable concrete material that may also promote futuristic energy and environmental stability of Palestinian buildings [13]. To the best of the authors' knowledge, the present study is considered the first study conducted in Palestine to investigate the use of PCB which is a by-product from a local pyrolyzed WTs plant located in Jenin city. Herein, four major tests are conducted by following the international standards. These tests are; slump, compressive strength, water absorption, and abrasion (friction loss). Consequently, a comprehensive relationship is developed among numerous parameters to investigate the performance of carbon black-based concrete. Therefore, utilizing PCB in concrete would allow us to reuse it within an environmentally friendly route, and reduce the negative environmental footprint of pyrolyzed WTs.

2. Materials and methods

The ingredients of reference concrete mix design are prepared to meet a standard of 30 MPa cubic compressive strength. Different percentage ratios of PCB/c are added to the reference mix design. Herein, the elemental composition of PCB, as the point of interest, is obtained to investigate the enhancement possibility of adding PCB. Additionally, around 90 cubic specimens of concrete, with dimensions of $10 \times 10 \times 10cm$, are prepared, mixed, and tested following international standards [51–54] according to the following subsections.

2.1. Pyrolyized carbon black (PCB)

One local source of PCB waste is considered in this study to achieve consistency of samples, and results. PCB, a by-product that is produced from the pyrolysis process of WTs, is provided by Al-Khaldi Factory in Jenin, West Bank, Palestine. The PCB sample is used without any treatment. According to predetermined experiments, the specific gravity of the used PCB was around 0.64, while its particle size was varied between 75 μm and 600 μm in which the average particle size was around 400 μm. In addition, the elemental composition, by %wt., for the PCB is analyzed and summarized in Table 1 [15].

2.2. Concrete compositions and specimen preparation

Concrete is mixed according to the following weight portions (1.0: 2.3: 4.0) to obtain a typical concrete cubic compressive strength of 30 MPa, which is equivalent to 24 MPa cylindrical compressive strength. This compressive strength is widely used for concrete in slabs and walls. Mix design consists of the following components: cement, water, sand, aggregates, and polycarboxylate based high-range water-reducing; superflow – G7, hereinafter, known as superplasticizer (SP), purchased from Protex-A-Cote international company (Jerusalem). All properties as well as the MSDS are shown in the supplementary material. A consistent w/c ratio of 0.5 is used for all samples besides SP to increase the workability of the concrete mix. Three types of aggregates are used; coarse (18−25) mm, medium (7−17) mm, and fine (1−6) mm as shown in Table 2.

2.3. Mixing pattern

Several studies investigated the addition of crumb rubber, carbon nanotubes, and engineered carbon black to cement/concrete with low ratios (up to 10%) [55–57]. Thus, a set of different percentages ratios of PCB/c are added to the reference mix to investigate the optimal ratio. Total of seven different weight percentages of PCB/c ratios (0%, 3%, 3.5%, 4%, 4.5%, 5%, 7%, and 10%) are used in this study, in addition to the reference mix (control sample). These PCB/c ratios are also selected based on preliminary results that assure the influence of adding PCB/c ratios ranging between 3% and 5%. As mentioned earlier, the range of PCB/c ratio is extended to 10% to formulate a clearer picture. Concrete mixes are thoroughly prepared by a mixture machine. Besides, sand, aggregates, and water are mixed according to BS EN 12350–1:2019 standards [51]. Finally, PCB is added and mixed for 3 min. Samples are prepared and cured according to another standard BS EN 12390 – 1:2012, 2:2019 [51,58], in addition to ASTM C 172 [59]. Concrete samples are prepared for compressive strength test at 7 and 28 days, water absorption test, and abrasion test as will be discussed in the next section.

Table 1
Elemental composition (wt%) and other properties of pyrolyzed black carbon (PCB) [15].

		PCB (%)
Elemental Composition	Carbon[a]	95.42 ± 0.16
	Hydrogen[a]	0.77 ± 0.20
	Nitrogen[a]	0.22 ± 0.07
	Sulphur[a]	3.29 ± 0.09
	Calcium[a]	0.19 ± 0.01
	Oxygen[a]	0.12 ± 0.07
Other Properties	Ash	16.55 ± 0.34
	Moisture	1.16 ± 0.14
	Volatile matter	2.50 ± 0.74
	HHV[b] (MJ/kg)	28.70 ± 0.18

[a] Results in dry basis and ash-free.

[b] Higher Heating Value.

Table 2
Mix proportions of concrete mixes.

PCB	Cement	Water	Sand	Aggregates	PCB	SP
%	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**
0	334.1	167.0	768.4	1346.3	0.0	6.8
3	335.9	167.9	772.5	1353.5	10.1	6.7
3.5	331.3	165.6	761.9	1335.0	11.6	6.6
4	332.7	166.4	765.2	1340.8	13.3	7.1
4.5	335.1	167.6	770.7	1350.5	15.1	6.9
5	334.6	167.3	769.7	1348.6	16.7	6.7
7	336.2	168.1	773.3	1355.0	23.5	6.6
10	333.9	166.9	767.9	1345.5	33.4	6.7

2.4. *Laboratory tests*

A set of mechanical tests are conducted considering basic properties of fresh and hardened concrete including; slump test of fresh concrete, compressive strength at 7 and 28 days, in addition to the water absorption and abrasion tests. Testing of specimens follows international standards as listed in Table 3.

Moreover, Fig. 1 summarizes the methodology of the research, starting with the production of PCB and reference concrete mixed up to evaluate the use of PCB as an additive in concrete mixes and draw qualitative and quantitative research outcomes.

The experimental procedure for each test shown in Table 3 and Fig. 1 is detailed as follows:

- **Slump test:** molds were prepared and filled with fresh concrete and tamped with a standard number of strokes per layer according to the mentioned specifications [51]. This is conducted to evaluate the concrete specimens' rheology and their slump reduction percentage with waste PCB as a binding material.
- **Compressive strength test:** After preparing the concrete samples, a compressive test was conducted according to the standard BS EN 12390–3&4:2019 [52]. Forty-eight concrete cubes, with dimensions of 10 × 10 × 10 cm, were prepared, in which 6 cubes are considered as control samples and the rest were distributed equally considering the PCB percentage variation. The mixes were fully immersed in water for a period of 7 and 28 days for curing since concrete materials are known to gain strength slowly at the early days of curing [60,61]. Afterward, the samples were placed in the compression machine (MATEST 24048, model number YIMC109NS, Treviolo, Italy). Loadings were applied and increased until the failure of the samples and the readings were obtained directly from the apparatus with a unit of MPa.
- **Water absorption test:** The experimental procedure for the water absorption test was conducted as per the standard ASTM C642 [53]. In brief, the concrete mixes were immersed in water for 28 days and then taken out and dried in an oven at 110°C for 24 h. Dry weights of the mixes were determined (D). Afterward, the mixes were immersed in water for 24 h and after surface drying, wet weights were determined (W). These experiments were conducted thrice to ensure reproducibility. The water absorption percentage was calculated as per the following equation:

$$Water \quad absorption \quad (\%) = \frac{W(g) - D(g)}{D \quad (g)} \times 100\% \tag{1}$$

- **Abrasion test:** this test is conducted according to the standard ASTM C131 [54] using the Los Angeles abrasion machine (MATEST 24048, model number YGM12168, Treviolo, Italy) at a speed around 33 rpm (500 revolutions for 15 min). The abrasion resistance percentage was calculated as per the following equation:

$$Abrasion \quad resistance \quad \% = \frac{W_i(g) - W_f(g)}{W_i(g)} \quad \times \quad 100\% \tag{2}$$

where W_i is the initial sample weight, and W_f is the final sample weight.

3. Results and discussion

The effects of adding PCB to the concrete mixes are discussed in terms of the basic properties of fresh and hardened concrete. This

Table 3
Test performed and relevant standards.

Test	Standards followed	Number of tested samples	Reference
Slump	BS EN 12350–2:2019	8	[51]
Compressive strength	BS EN 12390–3&4:2019	48	[52]
water absorption	ASTM C642	24	[53]
Abrasion (Friction loss)	ASTM C131	9	[54]

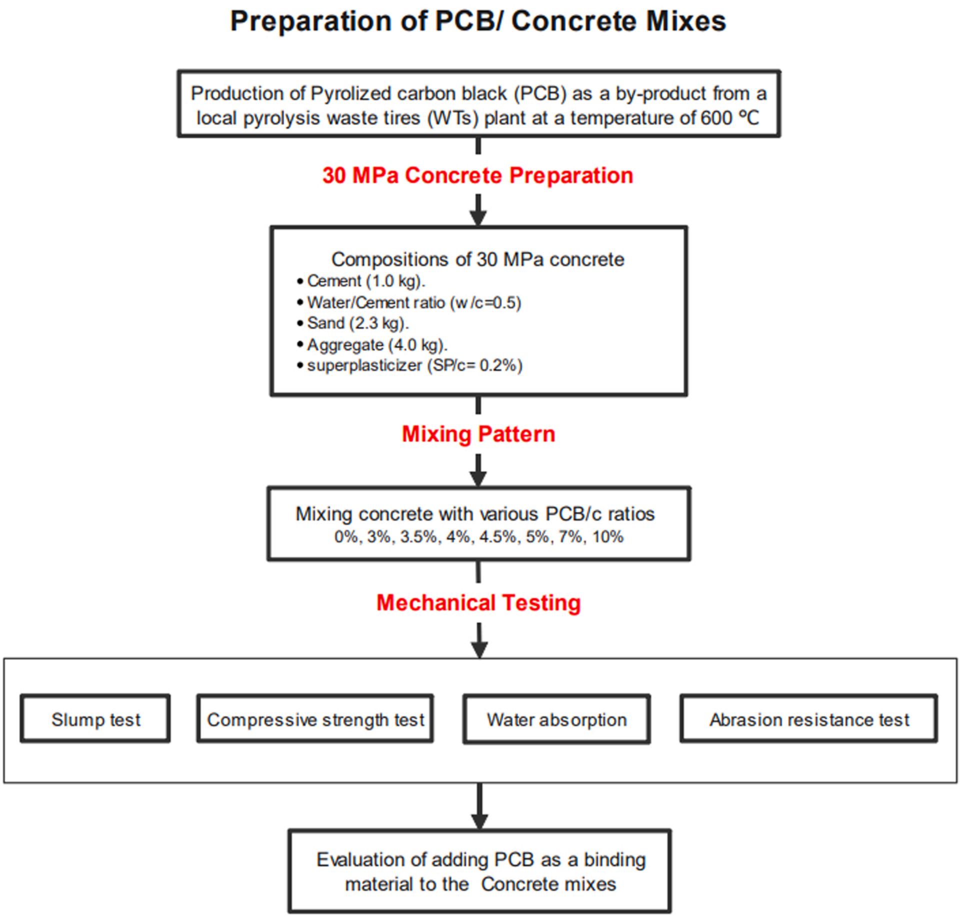

Fig. 1. Schematic flowchart of the current research approach.

includes testing the workability of fresh concrete using the slump test. In addition, the compressive strength of concrete at 7 and 28 days is tested as one of the main basic design criteria for any structural design. Water absorption and abrasion tests are performed also to evaluate the sustainability of the concrete mixes. Tests are conducted for the seven different PCB/c ratios and compared to the reference mix.

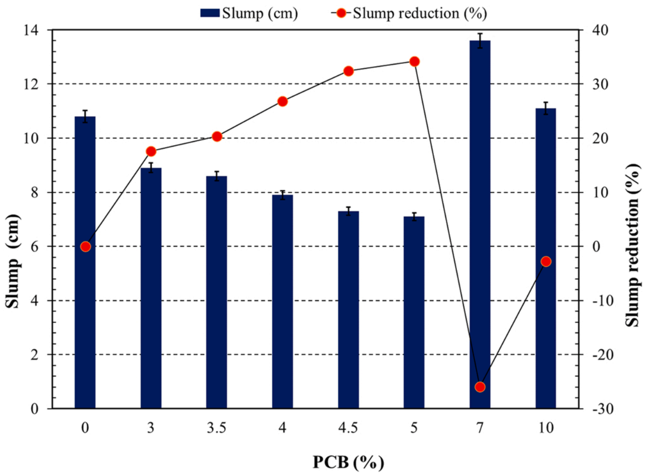

Fig. 2. Slump values for various percentages of PCB/c ratios.

3.1. Slump test

Fig. 2 shows the slump readings in correspondence with the reduction in slump values. The slump value for the reference specimen is 10.8 cm while increasing the PCB/c ratio decreases the slump by a mostly linear pattern up to 5.0%. This corresponds to around 34% reduction in slump value. However, the slump readings, even at PCB/c ratio of 5.0%, are still within the acceptable range of workable concrete for most applications as the slump is greater than 7.1 cm. Beyond PCB/c ratio of 5.0%, a considerable increase of slump values is noticed. For instance, Ali et al. [4] witnessed a noticeable increase in slump values upon partial replacement of fine aggregates with PCB up to 75% and then sharply decreased once a full replacement was reached. In addition, Elyamany et al. [62] who studied two groups of fillers; pozzolanic and non-pozzolanic noticed oscillation of slump values depending on the filler types. Herein, the increase in the slump values at higher dose percentages of PCB (7% and 10%) could be attributed to the aggregation of PCB. Based on these results, all concrete mixes with the different PCB/c ratios are workable for structural applications, however, the properties of hardened concrete must be tested to examine the validity of using all the mentioned ratios. This will be discussed in the coming sections.

3.2. Compressive strength test

The compressive strength of any concrete mix is considered as one of the key points that judges the efficiency of the hardened concrete properties. A total of 48 specimens are prepared for concrete compressive test considering the demanded ratios of PCB/c and tested using the compression strength testing machine. Half of the specimens are tested at 7 days while the second half is tested at 28 days to figure out the progress of gaining compressive strength and to compare them with reference specimens. As shown in Fig. 3 and Table 4, the compressive strength tests at 7 and 28 days show a consistency of gaining compressive strength for all specimens with different PCB/c ratios. This indicates that the use of concrete with PCB will have the same design strategy of casting concrete and removing formwork as normal concrete. Since the gained strength of concrete with PCB at 7 days compared to 28 days is relatively the same as for normal concrete. In other words, the ratio of 7–28 days compressive strength for reference specimen is 0.73, interestingly, this ratio is approximately gained for the other specimens. The use of PCB with different percentages of PCB/c ranging between 3% and 5% provides concrete an extra compressive strength between 14% and 26%. The maximum extra strength is achieved by using 4.0% PCB/c ratio. Experiments showed a slightly negative impact of using PCB beyond 9.0% of PCB/c ratio. The density of specimens is not affected by using PCB, therefore concrete has, approximately, same own weight. These results go in line with some findings published elsewhere [25,57,63]. For instance, Wen and Chung [63] noticed upon replacing around 50% of its content with carbon black within cement-matrix composites, the compressive strength maintained its value. However, Rezania et al. [25] observed an initial decrease in the compressive strength of the concrete upon adding the nanocarbon black (0.4 and 0.8 wt%). Notwithstanding, a clear increase in compressive strength was obtained upon adding 1.2 wt% of nanocarbon black. The authors attributed this behavior to filling concrete pores which causes an increase in the compressive strength. Accordingly, this phenomenon is witnessed in this study upon adding up to 4.0 wt% of PCB. This perfectly lines up with the study conducted by Monteiro et al. [57], as the authors not only observed the same trend of compressive strength also obtained the highest compressive strength value upon adding 4.0 wt% of Orion engineered carbon black.

3.3. Water absorption test

As mentioned earlier the standard ASTM C642 [53] is employed to measure the water absorption. Dry and wet weights of specimens are measured to calculate the water absorption. The addition of PCB/c is expected to have a positive impact on the reduction of water absorption percentage for all specimens (Fig. 4). At the same time, water absorption and compressive strength results are

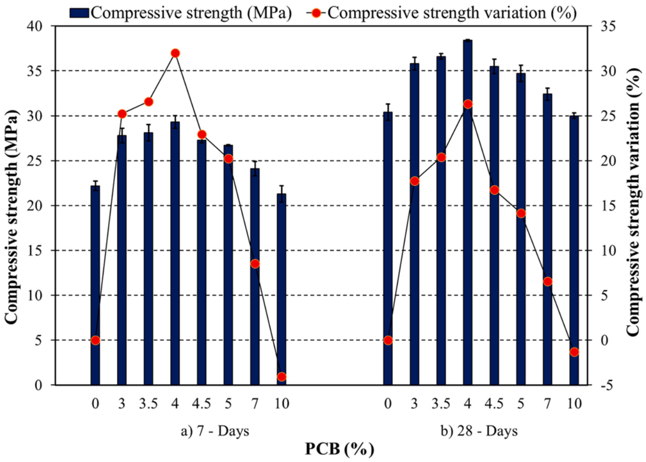

Fig. 3. Average compressive strength results determined at various percentages of PCB for a) 7-days and b) 28-days.

Table 4
Compressive strength at 7 and 28 days for various percentages of PCB.

PCB/c (%)	7-days			28-days		
	Weight (g)	Density (g/cm^3)	Compressive strength (MPa)	Weight (g)	Density (g/cm^3)	Compressive strength (MPa)
0.0	2379.8	2.3798	22.5	2153.2	2.1532	30.3
	2364.2	2.3642	21.9	2204.0	2.2040	30.1
	2391.7	2.3917	22.3	2132.3	2.1323	31.0
	2378.5	**2.3785**	**22.2**	**2163.1**	**2.1631**	**30.4**
3.0	2297.1	2.2971	28.2	2198.0	2.1980	35.6
	2264.8	2.2648	27.3	2203.0	2.2030	36.3
	2201.4	2.2014	27.9	2245.0	2.2450	35.7
	2254.4	**2.2544**	**27.8**	**2215.3**	**2.2153**	**35.8**
3.5	2431.8	2.4318	28.6	2234.0	2.2340	36.7
	2350.4	2.3504	28.1	2265.3	2.2653	37.2
	2387.2	2.3872	27.8	2301.2	2.3012	35.9
	2389.8	**2.3898**	**28.1**	**2266.8**	**2.2668**	**36.6**
4.0	2294.1	2.2941	29.5	2134.3	2.1343	38.9
	2243.5	2.2435	29.8	2198.2	2.1982	38.7
	2322.3	2.3223	28.8	2204.9	2.2049	37.6
	2286.6	**2.2866**	**29.3**	**2179.1**	**2.1791**	**38.4**
4.5	2345.1	2.3451	27.9	2145.8	2.1458	36.2
	2346.8	2.3468	27.3	2213.4	2.2134	35.4
	2537.6	2.5376	26.8	2156.9	2.1569	35.1
	2409.9	**2.4099**	**27.3**	**2172.0**	**2.1720**	**35.5**
5.0	2375.2	2.3752	26.8	2237.4	2.2374	34.2
	2403.9	2.4039	27.1	2352.1	2.3521	34.9
	2418.1	2.4181	26.2	2146.8	2.1468	35.0
	2399.1	**2.3990**	**26.7**	**2245.3**	**2.2453**	**34.7**
7.0	2342.8	2.3428	24.1	2453.2	2.4532	31.4
	2431.3	2.4313	23.8	2231.1	2.2311	32.8
	2452.6	2.4526	24.5	2230.3	2.2303	33.1
	2408.9	**2.4089**	**24.1**	**2304.8**	**2.3048**	**32.4**
10.0	2315.3	2.3153	21.3	2312.3	2.3123	29.8
	2456.1	2.4561	21.9	2201.1	2.2011	30.3
	2234.2	2.2342	20.8	2356.2	2.3562	29.9
	2335.2	**2.3352**	**21.3**	**2289.8**	**2.2898**	**30.0**

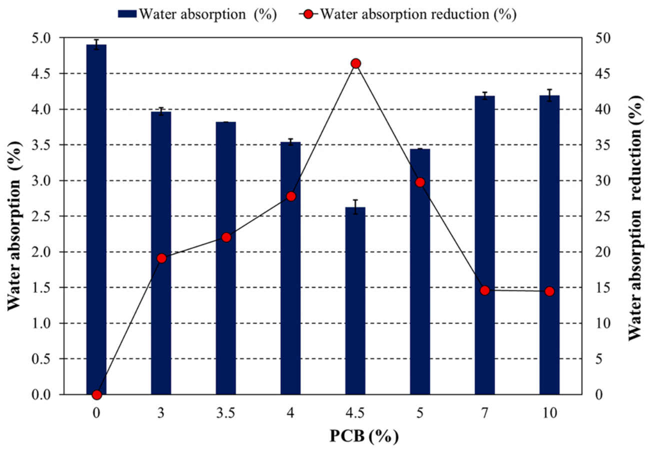

Fig. 4. Average water absorption test values attained for concrete specimens at various percentages of PCB.

consistent which assure that mixes in the range of 4–5% of PCB/c ratios have the maximum positive impact for both tests. Beyond the PCB/c ratio of 5%, water absorption results track the compressive strength results (Fig. 3). Table 5 and Fig. 4 clearly show the drop in the water absorption reduction from 47% at PCB/c ratio of 4.5–14% at PCB/c ratio of 7%.

In addition, during the experimental testing, visual observation indicates more condensation of concrete specimens as a result of the presence of PCB as an additive in the concrete mix. This result resembles the previous findings proposed by Rezania et al., [25]. The existence of PCB in concrete mix leads to fill voids, thus, reducing the concrete porosity, increasing the compressive strength, and causing a reduction in water absorption. However, it is worth mentioning that at high percentages of PCB, the compressive strength and water absorption reduction start decreasing. This is a result of the additional carbon bonds, which are relatively weak. A similar

Table 5
Water absorption test values at various percentages of PCB.

PCB (%)	Dry weight (g)	Wet weight (g)	Water absorption (%)
0.0	2257.8	2368.3	4.89
	2127.7	2241.6	5.35
	2427.5	2536.2	4.47
	2271.0	**2382.0**	**4.90**
3.0	2158.8	2248.2	4.14
	2269.9	2356.0	3.79
	2307.1	2398.7	3.97
	2245.3	**2334.3**	**3.97**
3.5	2365.6	2453.3	3.7
	2485.1	2571.7	3.48
	2057.4	2145.6	4.28
	2302.7	**2390.2**	**3.82**
4.0	2393.5	2481.6	3.68
	2510.2	2593.1	3.30
	2347.3	2432.8	3.64
	2417.0	**2502.5**	**3.54**
4.5	2474.8	2538.4	2.56
	2430.3	2498.7	2.81
	2533.7	2597.3	2.51
	2479.6	**2544.8**	**2.63**
5.0	2358.9	2438.1	3.35
	2314.3	2394.7	3.47
	2167.5	2243.6	3.51
	2280.2	**2358.8**	**3.44**
7.0	2217.4	2314.3	4.36
	2313.5	2406.1	4.00
	2263.1	2358.2	4.20
	2264.7	**2359.5**	**4.19**
10.0	2427.4	2534.3	4.41
	2515.9	2617.8	4.05
	2578.1	2684.5	4.12
	2507.1	**2612.2**	**4.19**

observation was attained by Monteiro et al. [57], as they have noticed a decrease in the registered capillary tests (more than 50%) upon adding engineered carbon black (0 up to 10 wt%) as fillers due to closing the composite pores. So, in conclusion, these findings could be attributed to the change of the textural properties mainly; morphology and structure, upon mixing PCB with cement.

The above-mentioned tests confirm an effective increase of compressive strength and water absorption reduction for mixes with PCB/c ratio ranging between 4% and 5%. In addition, compressive strength, as the basic property of concrete, reaches maximum strength at a 4% PCB/c ratio. Therefore, the upcoming abrasion test is performed for the 4% PCB/c ratio in addition to the reference mix and an extreme ratio of 10%.

3.4. Abrasion resistance test

The abrasion test evaluates the frictional characteristics together with abrasion resistance. This is one of the tests that evaluate sustainable characteristics of concrete. The standard of ASTM C131 [54] is employed to measure abrasion resistance. As stated in the previous section, this test is conducted for the control sample, PCB/c of 4.0%, and PCB/c of 10%. The friction loss of specimens is measured by weighting specimens before and after the test and calculating the percent of weight loss as indicated in Table 6.

Table 6
Results of the abrasion resistance test at various percentages of PCB.

PCB (%)	Weight before friction (g)	Weight after friction (g)	Abrasion resistance (%)
0.0	2231.0	2224.0	0.31
	2212.0	2206.0	0.27
	2221.0	2213.0	0.36
	2221.3	**2214.0**	**0.32**
4.0	2086.0	2083.0	0.14
	2142.0	2140.0	0.09
	2162.0	2160.0	0.09
	2130.0	**2127.6**	**0.11**
10.0	2078.0	2070.0	0.44
	2120.0	2109.0	0.44
	2129.0	2118.0	0.38
	2109.0	**2090.0**	**0.47**

The results of the abrasion test shown in Fig. 5 reflect the effectiveness of PCB/c ratio of 4% on decreasing friction loss. This confirms that this ratio is the optimal one in increasing characteristics of hardened concrete that also matches the workability requirements.

Eventually, it is important to check the competency of the prepared concrete mixes with other published studies. Thus, Table 7 lists findings from the literature where carbon black was obtained from different resources and incorporated in the concrete structure with specified ratios, to form mixes with improved mechanical properties. On one hand, the methods of utilizing carbon black can be through the partial or complete displacement of certain constituents in the structure such as sand, virgin aggregates, silica fume, etc. On the other hand, it can be combined with other resources to modify some features such as compression strength, split test, failure tests, slump reduction, and water absorption. Notably, this study showed a clear, yet competent, enhancement in some mechanical properties at an optimal PCB/c ratio of 4%. This indicates the promising additives of PCB in the concrete industry.

4. PCB waste management in Palestinian territories

This research is oriented towards adopting sustainable construction based on the concept of solid waste-to-product management in the Palestinian Territories by recognizing the significant adverse impact of WTs and cement on the environment. However, still, the developing countries, like Palestine, are encountering many problems that hinder their development process, most commonly because of the lack of awareness and interest in such topics, and adaptation of such approaches through institutional legislation. Alongside, the United Nations 2030 Agenda for Sustainable Development calls for the exigency of giving attention to environmental sustainability, social development, and economic growth [68,69].

The large number of tiers produced each year is a naturalistic result of the industrial expansion in the transportation sector. Recently, government officials have called for the importance, and urgency, of exploring alternative approaches to manage WTs to reduce the impact on the environment, while increasing the efficient usage of natural resources [68]. Indeed, several approaches have been made, among those is the pyrolysis process and the eco-designing of concrete by utilizing PCB in the concrete industry. In this context, the research at hand contributes to this literature area. More specifically, we utilize the institutional perspective as our theoretical anchor to explore how to drive the adoption of PCB as an additive, to create eco-friendly and sustainable concrete products.

The utilization of institutional theory can aid policymakers in exploring the institutional environment that facilitates the adoption of PCB in the concrete industry. The theory suggests that firms are widely influenced by actors residing within their external environment [70–72]. The environment comprises specific norms, regulations, and values [68]. These institutional pressures guide, and sometimes restrain, firms' behaviors and performance. Therefore, firms will eventually abide by these institutional elements. They will adapt their operations to fit the institutional context they operate in, i.e., isomorphic with their context, to survive and gain legitimacy [68,70,71,73,74].

Institutional pressures can be classified into three types, i.e., coercive, normative, and memetic [70,72]. Depending on the context, these institutional pressures may emerge from, or enforced by, different stakeholder groups such as governments, customers, suppliers, industry associations, non-governmental organizations, and communities [68]. In addition, these pressures can change firms' business practices [72], streamline their operations in the industry, while regulating their behaviors. Policymakers can utilize the three types of institutional pressures to enforce firms to eco-design their products, e.g., using PCB as an additive, with the ultimate aim of creating eco-friendly concrete industry.

Firstly, coercive pressure arises when stakeholders impose stringent and mandatory rules, standards, and regulations that firms need to follow to operate. It is usually created by influential and powerful stakeholders such as governmental and local authorities. In our context, authorities can play a leading role in the adoption of PCB across the concrete industry. They can enforce specific regulations and policies to oblige the industry to use PCB as an additive in the production processes. Firms in the concrete industry will

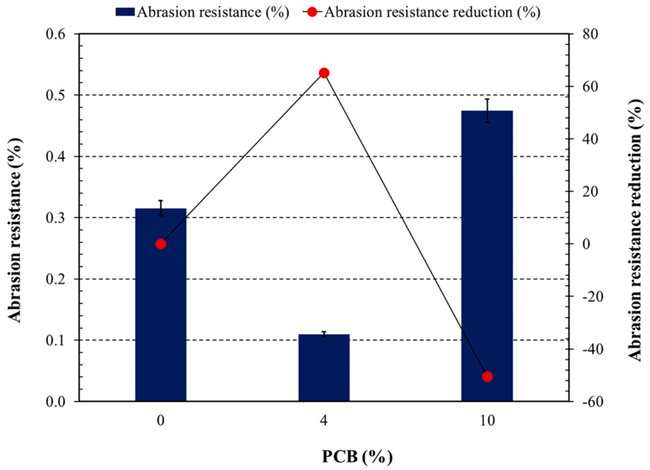

Fig. 5. Average abrasion resistance at all percentages of PCB.

Table 7
Comparison of different synthesized carbon black/concrete composites.

Source	Composite ratiocarbon black/ concrete	Method	Mechanical properties	Ref.
Waste tires pyrolysis	0, 25, 50, 75, and 100 wt%	Replacement of fine aggregate	• The replacement values were 25% and 50% and the corresponding strength of concrete varied from 20 to 18 MPa.	[4]
Pen 85/100 asphalt binder	10%, 20%, and 30%	Marshall mixes design method	• The effect of carbon black on the IDT peak strength and failure energy of the siliceous-based composite was higher than that of the limestone-based composite. • Carbon black with 10% (wt. of the asphalt binder showed higher uniaxial compression strength and displacement at intermediate temperature.	[64]
Carbon black from styrene–butadiene–styrene (SBS)	Carbon black mixed with 70/100 penetration grade bitumen.	Partial replacement of virgin aggregates	• A slight increase in the stiffness in the presence of carbon black compared with commercial polymer-based bitumen. • The mixture of carbon black polymer-modified bitumen showed increased cohesion according to the water sensitivity test.	[65]
Colloids obtained from incomplete combustion or thermal decomposition of liquid or gaseous hydrocarbons.	• Nano-carbon black replacement to reinforced concrete specimens (0.4%, 0.8% and 1.2%) • Nano-silica reinforced concrete specimens' replacement (0.2%, 0.4% and 0.6%) • Hybrid concrete specimens (containing both nano additives)	Partial replacement of concrete	• Slump reduction will be higher when incorporating both nanoparticles when compared with using each one solely. • Compressive tests show that strength increases by adding the nano-silica and initially decreases when adding nano-carbon black. When both compounds are used, the strength decreases to a certain percentage of nano-carbon and then increases. • Permeability is reduced by replacing cement with nanoparticles.	[25]
Commercial carbon black and carbon fiber.	• Carbon black content used ranged from 0.5% to 2.0% by mass of cement. • Carbon fiber content used ranged from 0.5% to 3.5% by mass of cement.	Partial replacement of carbon fiber by carbon black	• Both the conductivity and the shielding effectiveness diminish upon the total replacement of carbon fiber by carbon black. Also, the compressive modulus greatly decreases. • The addition of carbon fiber to cement in presence of carbon black decreases the compressive strength, strain at failure, and density.	[63]
Polyethylene terephthalate (PET), polyvinyl chloride (PVC), and black and grey materials.	• Solid recovered fuels (SRF) ash substitutes' small part of the raw materials required for cement clinker production.	Partial replacement	• One of the aims of this work is to enable the production of a contaminant-depleted SRF in concrete industries.	[66]
Carbon black products of a local petrochemical plant and Cabot, UK.	• Water/binder ratios from 0.2 to 0.50	Silica fume was replaced by carbon black	• Carbon black is effective in modifying the basic concrete-matrix strength when its particle size was smaller than 0.073 μm giving 10 MPa related strength.	[67]

(*continued on next page*)

Table 7 (*continued*)

Source	Composite ratiocarbon black/ concrete	Method	Mechanical properties	Ref.
Waste tires pyrolysis	PCB to concrete ratio ranged from 0% to 10%	Mixing according to BS EN 12350–1:2019 standard	• Carbon black is an inert filler in the concrete-matrix. • PCB/c ranging between 3% and 5% provides concrete a significant compressive strength between 14% and 26%, respectively. • Water absorption reduction from 47% at PCB/c ratio of 4.5–14% at PCB/c ratio of 10%. • An increase in abrasion resistance at PCB/c ratio of 4%.	This Study

conform to these standards and policies to be able to operate, i.e., survive, and avoid potential penalties for non-compliance. Coercive pressures from powerful stakeholders can shape the external environment [72,74], while controlling/regulating the operations of the entire industry.

Secondly, normative pressure arises due to stakeholders' expectations, such as customers' and suppliers' values, community norms, industry associations' schemas, and non-governmental organizations' assumptions. These values and assumptions can play a vital role in promoting the adoption of the PCB across firms' production facilities and operations. Indeed, not following these expectations will influence companies' economic benefits and the reputation of the entire industry. For example, customers may decide not to buy products from companies that do not use PCB in their production processes, which will eventually impact the financial performance of companies in the concrete industry. In addition, industry associations may establish various schemas to protect the environment, e.g., the utilization of PCB. Concrete providers should follow these schemas to operate. Any non-compliance to schemas may lead to loss of membership in these associations. Companies that are unwilling to meet stakeholders' expectations may not be able to survive in the long term.

Thirdly, mimetic pressure arises due to the uncertainties in the environment [68,70]. Therefore, companies may attempt to imitate the practices and behaviors of main players/rivals in the industry [72]. This is specifically true when firms believe that the adoption of these practices is a potential source of competitive advantage. For example, if main players adopted PCB in their production processes, other competing firms would follow the same steps and imitate exemplar firms' operations by adopting PCB to sustain their competitive advantage and gain superior performance.

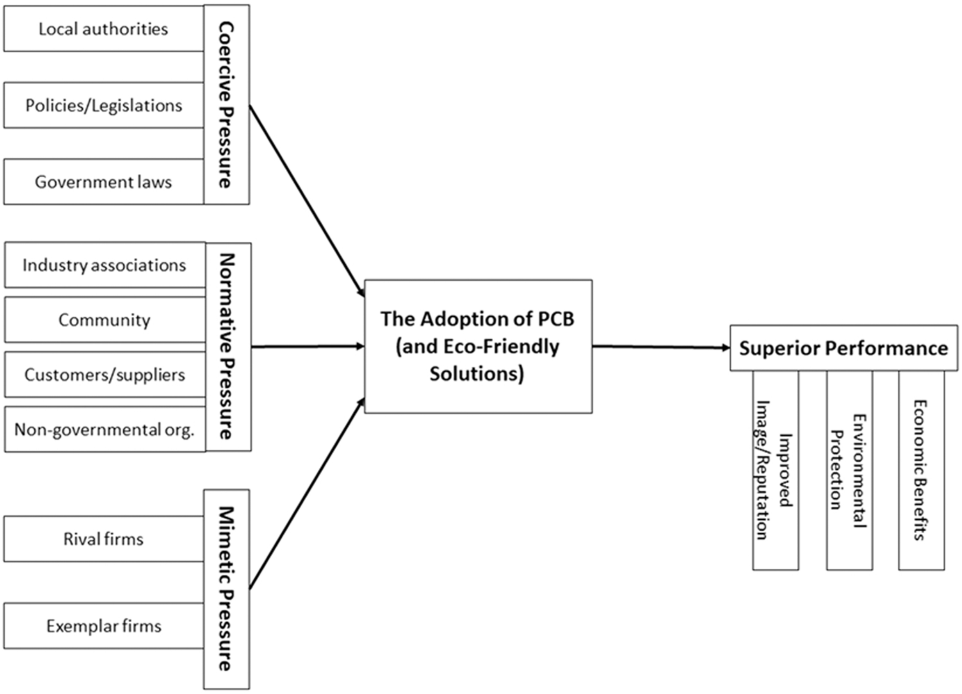

Fig. 6. Multi-level framework on the impact of institutional pressures on the adoption of PCB as an additive.

Eco-designing concrete products by utilizing PCB as an additive is recognized as a valuable approach for waste management. The research concludes that different institutional drivers have a positive impact on PCB adoption across the concrete industry, i.e., coercive, normative, and memetic. Firms in the concrete industry that are under increased institutional pressures will attempt to eco-design their products and adopt PCB across their production processes in order to gain superior performance and legitimacy, in addition to maintaining decent relations with stakeholder groups [68].

It is worthy to note that at early stages, coercive pressures may play a crucial role in the adoption of PCB in the concrete industry, specifically if they are established by influential stakeholders such as the government. Governmental and local authorities can have a significant impact on firms' environmental practices and decisions. Pressure may evolve over time, meaning that normative and mimetic pressures from industry associations, customers, suppliers, associations, and even competitors will promote firms in the concrete industry to co-design their products and use eco-friendly solutions. Fig. 6 depicts a multi-level framework for the adoption of PCB in the concrete industry. Though empirical investigations are needed to validate the framework, which can be utilized to investigate the adoption of other eco-friendly solutions in different industries.

To summarize, coercive, normative, and mimetic pressures spur firms in the concrete industry to construct their products while changing their environmental practices and behaviors. The institutional theory provides a potential exploration of PCB adoption across the concrete industry. Firms that can design eco-friendly solutions may cultivate superior benefits. They can reap superior economic performance through improved reputation and increased customer orders. Giving little attention to stakeholder perception and resisting their expectations may eventually cause damage to their competitive advantage in the industry.

The findings in this research have implications for decision-makers. More specifically, instead of introducing the technical features of PCB when it is utilized as an additive in concrete products, thus, decision-makers can promote the adoption of PCB by institutionalizing various legislations and enforcement laws (coercive). They can demonstrate the superior benefits that exemplar firms have gained from the adoption of eco-friendly solutions such as PCB (mimetic). They can collaborate with non-governmental organizations and industry associations, influence customers' perception of the importance of using eco-design concepts in the environment; therefore, creating (normative) pressure on firms in the concrete industry to adopt PCB (and sustainable solutions) in their operations.

5. Conclusions

Environmentalists and engineers are striving nowadays to promote the green concrete industry into buildings and construction materials to reduce the environmental footprints of the cement and concrete industry. Therefore, in this study, the use of pyrolyzed carbon black (PCB), produced from waste tires, as an additive material in the production of structural concrete has been investigated.

A set of samples were prepared and tested following international standards considering different ratios of PCB to cement (PCB/c) ranging from 0% (control sample) to 10%. The results of this study showed promising enhancements regarding concrete mechanical properties mainly slump, compressive strength, water absorption, and abrasion resistance. Based on the findings of this research, the following conclusions are drawn:

- All slump measurements showed workable PCB/c mixes. However, the workability of concrete with PCB was minimal at PCB/c ratio of 4.5%.
- The use of PCB as an additive material in different concrete mixes improved the compressive strength of concrete. The maximum values of 29.3 and 38.4 MPa were obtained at a ratio of 4% for 7 and 28 days, respectively. Although, this percentage was the optimal value, however, using higher percentages has limited this property due to weak bindings resulting from excess void fillings.
- The results of water absorption and abrasion resistance tests were consistent with each other as evidently the hardened concrete properties were enhanced by using PCB/c at around 3 – 5%.
- The research outputs of this study along with its management perspective as well as the comparative analysis with literature reveal the competent improvement of concrete properties that allow PCB/c mixes to be used for structural purposes.

In conclusion, using PCB waste in concrete as additive material by 4 – 5% of PCB/c ratio, within the used concrete portions in this study, is recommended for optimum properties of hardened concrete. Futuristic research efforts will focus on the replacement of concrete components by PCB and/or other waste carbon black sources utilizing the concept of sustainable and green concrete. It is also worth considering the effect of PCB particle size on such applications in the coming studies.

Declaration of Competing 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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