Research Article

Effect of industrial wastes on self-cleaning properties of concrete containing anatase-TiO₂

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Abstract: Concrete decomposing the organic compounds on because of natural or anthropogenic contaminating sources with photocatalysis existing in its structure is called self-cleaning concrete. In this study, the self-cleaning concrete with industrial waste has been searched from the point of mechanical and physical characteristics. Fly ash, blast furnace slag and sepiolite materials has been used as industrial waste in concrete. Titanium dioxide (TiO₂) has been used as photocatalysis material. Specimens with the dimensions 15×15×15 cm were produced using 0 %, 10 %, 20 % and 30 % industrial wastes and 0 %, 1 %, 3 %, 5 % TiO₂ by weight instead of cement. Compressive strength, unit weight, and ultrasonic pulse velocity tests were performed on the specimens after 28 days standard cure. Rhodamine-B test in Italian UNI 11259 standard and additional Phenantroquinone test have been performed as self-cleaning test. XRF test also has been made on some of the samples for the chemical analysis. The best photocatalysis performance has showed in the concrete including 5 % TiO₂. Test results show that 10 % use of industrial wastes in self-cleaning concrete production is recommended from the point of economic and environmental benefits.

Keywords: Photocatalysis, titanium dioxide, blast furnace slag, fly ash, sepiolite.

1. Introduction

Generally, the pollution occurring on the surfaces of the buildings is caused by atmospheric pollution, which is divided into two as human resources and natural resources. The development of photocatalytic systems, which will be effective in the elimination of these impurities, is of great importance (Gürbüz et al., 2009). The usage areas of the self-cleaning feature, which is one of the main application areas of photocatalysis, in construction building materials are gradually expanding. (Chen and Poon, 2009; Stamate and Lazar, 2007). Studies have shown that self-cleaning concrete decomposes contaminants containing NO_X, SO₂ etc. by photocatalytic reactions (Awadalla et al., 2011; Torgal and Jalali, 2011; Melo and Triches, 2012, Shen et al., 2015; Luna et al., 2020). Studies aimed at gaining photocatalytic properties of building materials by adding titanium dioxide (TiO₂) in cement, mortars or concretes and thus removing the surface of the building from contaminants (Krishnan et al., 2013; Pozo-Antonio and Dionisio, 2017). TiO₂ in photocatalysis reactions; due to its strong oxidation ability, longlasting resistance against corrosion and good dispersion, hydrophobicity, chemical stability, inert structure, non-toxicity, cheapness and light permeability, it is the most frequently studied and used material in applications (Chang et al., 2009; Affam and Chaudhuri, 2013; He et al., 2019). Concretes containing titanium dioxide, which has the feature of self-cleaning from

photocatalytic materials, not only clean its surface, but also help to clean the dirty air it is exposed to (Ramirez et al., 2012). By self-cleaning of these concretes, a great profit can be achieved by reducing maintenance costs (Hanus and Harris, 2013).

Photocatalysis is the degradation of organic compounds by reduction and oxidation reactions by means of a photocatalyst under UV light or visible light irradiation (Costa et al., 2013; Ferella, 2019). Semiconductor materials such as TiO₂ contain valence and conductivity bands in their atomic structures. If a photon is absorbed from the UV source or from the visible region of the electromagnetic spectrum at an energy greater than the band gap of the semiconductor material, an electron in the valence band is stimulated and leaps into the conductivity band, and the void of that electron is formed in the valence band. Thus, the reaction results in a stimulated electron (e⁻) - positive space (h⁺) pair. This pair of e⁻- h⁺ undergoes reduction and oxidation reactions of chemicals on the surface of the photocatalyst (Angelo et al., 2013; Nakata and Fujishima, 2012; Vasilache et al., 2013). As can be seen in Figure 1, photocatalysis reactions can degradate, but physical effects such as wind and rain are needed to remove them from the concrete surface. Figure 1 shows concrete surfaces with TiO₂ added (Delnavaz et al., 2015).

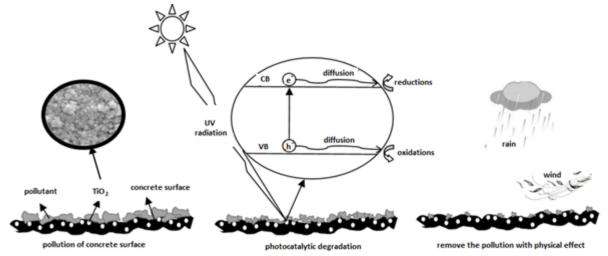


Figure 1. Mechanism of photocatalytic degradation.

In 1998, for the first time in history, self-cleaning concrete was used in a structure. The Jubilee Church in Rome, Italy, is the first building containing concrete with a self-cleaning feature. The use of photocatalysis in structures has increased and developed since this period (Hunger and Brouwers, 2009). In a study where the effect of TiO₂ size on photocatalytic reactions in concrete was investigated, it was stated that micro size TiO₂ showed better photocatalytic performance than nano size TiO₂ (Folli et al., 2009). In experiments using different ratios of TiO₂ on cement paste and mortars, maximum self-cleaning performance was achieved with the use of 5% TiO₂. Also, better results were obtained from cement pastes compared to mortars (Ruot et al., 2009; Chen et al., 2011). In case of using TiO₂ as a photocatalyst in concrete, it has been observed that the pollution caused by the nitric oxide and its derivatives present in the air exhaust and flue gas is removed by separating both on the concrete surface and in the air (Hüsken et al., 2009; Folli and Macphee, 2010; Lucas et al., 2013). In addition, it is stated that the carbonation resistance of 3 mm thick TiO₂ doped mortars applied on the reinforced concrete surface is increased and the corrosion spread rate of the concrete reinforcements is decreased (Fiore et al., 2013). Rhodamine-B is used as a pollutant in determining the self-cleaning performance (Calia et al., 2017; Guo et al., 2016). Phenantroquinone can also be used as a pollutant. These experiments can be carried out under artificial UV source in laboratory conditions, as well as in the open air to be exposed to external effects. In fact, it has been observed in the studies conducted that the pollutants disintegrated as a result of photocatalysis move away from the surface more easily in the open air (Yüksel and Karagüler, 2011). In order to increase the photocatalysis performance, there was an increase in the self-cleaning feature of TiO2 doped mortar and cement pastes modified with silicon, nitrogen and carbon compared to the control samples (Janus et al., 2015; Mendoza et al., 2015). It was observed that the waste glass did not have a negative effect on the self-cleaning performance of the concrete in the samples obtained by breaking the waste glasses into the concrete by breaking the grain size below 2 mm (Sikora et al., 2015).

1.1. Scope and significance

In this study, TiO₂ was used as photocatalyst and Rhodamine-B and phenantroquinone were used as pollutants as in most studies in determining the self-cleaning performance of concrete. Unlike other studies, the effect of industrial wastes on the self-cleaning performance of concrete was investigated in this study. Recent studies, usage of industrial wastes as a admixture in the concrete mixtures were investigated (Azevedo et al., 2020a; Azevedo et al., 2021). Some studies show that substitution of cement with the industrial waste has enabled to cut down the greenhouse gas emission and energy consumption (Yin et al., 2018; Silva et al, 2017). For this purpose, fly ash and blast furnace slag were used as industrial waste in gray cement concretes, and sepiolite was used in white cement concretes because of its close to white color. Some of the samples produced were exposed to external influences such as sun, rain and wind outdoors, while the other were exposed to artificial UV sources in the dark environment (Ünal, 2015).

2. Materials and methods

2.1. Materials

Cement: CEM I 42.5 R (gray) and CEM I 52,5 R (white) cements were used in the experiment. The physical and chemical properties of these cements are listed in Table 1. Fly Ash (FA): The entire experimental study was performed using F-type fly ash. The physical and chemical properties of the FA are listed in Table 1. Granulated Blast Furnace Slag (BFS): The entire experimental study was performed using slag from the Ereğli Company. The properties of the slag are listed in Table 1. Sepiolitte (ST): The entire experimental study was performed using ST from the Sakarya Mining Company. The physical and chemical properties of the ST are listed in Table 1.

Table 1. Properties of materials and mixture ratios.

Content %	CEM I 42.5 (Ordinary) (EN 197-1)	CEM I 52.5 (White) (TS 21)	FA (EN 450-2)	BFS (EN 197-4)	ST (TS 12131)
CaO	63.56	65.64	4.28	30.82	1.28
SiO_2	19.25	21.60	53.71	34.09	59.65
Al_2O_3	5.05	4.28	22.4	12.19	1.56
Fe_2O_3	2.56	0.24	10.6	0.61	0.74
Spec. gravity	3.1	3.12	2.02	2.84	2.21
Fineness,cm ² /g	3320	4100	2220	2230	2570

Aggregate: In this study, crushed sand (0-4 mm) and crushed stones (4-16 mm, 16-32 mm) were employed. TiO_2 : TiO_2 was obtained from the Detsan company. The properties of TiO_2 are listed in Table 2.

	Ta	ble 2. Properties of TiO _{2.}	
Form	Spec. gravity	Fineness, m ² /g	Size distribution, nm
Anatase	4.1	85	15-25

Water: Eskişehir tap water was used. The chemical analysis of the drinkable water is displayed in Table 3.

Table 3. Chemical analysis of the water (mg/dm ³).								
pН	NH_4	Mg	Fr	SO_4	P	As	Fe	NO_3
8.00	0.07	0.002	31.43	78	0.06	3.57	0.005	8.80

2.2. Methods and tests

In concrete mixture, 0, 10, 20, and 30 % by weight (wt %) industrial wastes replaced with cement were used. In this study; fly ash, blast furnace slag and sepiolite were used as industrial waste. In the studies conducted in the literature, it has been seen that the usage rate of industrial waste materials is up to 30% of the cement weight (Topçu and Canbaz, 2007). TiO_2 was added into concrete mixtures as a photocatalyst 0, 1, 3, and 5 % by weight (wt %) of cement. Concretes were produced using mix ratio of concrete ingredient shown in Table 4. Slump test performed on each type of concrete mixture. $15 \times 15 \times 15$ cm specimens of each mixture were prepared. Concrete specimens were cured in standard conditions until 28-day. Unit weight, ultrasonic pulse, and compressive strength tests were performed. Effects of industrial waste and TiO_2 on concrete properties were determined with these tests.

Table 4. Mixture ratio by weight.

Water /	Cement/	Additive/	TiO ₂ /		Aggregate mix	xture	
binder	aggregate	cement	cement	0-4 mm	4-16 mm	16-32 mm	
0.550		0.00	0.00		30%		
	0.222	0.10	0.01	500/		20%	
	0.232	0.20	0.03	50%			
		0.30	0.05				

For determining self-cleaning performance, tests were made with pollutants like Phenantroquinone and Rhodamine-B according to Italian UNI 11259 standard (UNI 11259, 2008). A solution with 0.05 g/l concentration resoluble Rhodamine-B was prepared for the Rhodamine-B tests. 1 ml solution applied to 3.5×7 cm² area on the surface of specimen. These specimens cured at 20 °C and 50 % relative humidity in the unilluminated condition for 24 hours. Reference colorimetric measurements were carried out on dyed surfaces with spectrophotometer, which measures directional $65^{\circ}/10^{\circ}$ and diffuse $8^{\circ}/d$ sphere geometry, according to CIE L*a*b* color system. CIE is an organization that aims to establish basic standards and methods for measurements in the fields of light and illumination. Many different color systems are used in the CIE color system, named after the organization. In this experiment, the L*a*b system required in the Italian codes was used. In this system, L* indicates lightness, a* is the red/green coordinate, and b* is the yellow/blue coordinate as shown in Figure 2.

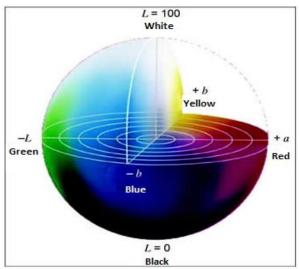


Figure 2. L, a, b color plane in the CIELAB system.

In this study, a* calorimetric coordinate was considered due to the use of red color Rhodamine-B. After these processes, 300 watts of UV light (osram) were exposed to light. All test samples were placed equidistant to the UV source and approximately 75 cm. Then, a (26) colorimetric readings of concrete samples kept under UV light were made during the 26-hour period. After these processes, concrete samples were exposed to UV light for 28 days. At the end of 28 days, a (s) values were read. As can be seen in Figure 3, the color formed by Rhodamine-B chemical is supported by colorimetric readings, which over time fade with UV light source. Similarly, in phenantroquinone experiment, phenantroquinone solution was applied to the sample surface and after waiting

for 24 hours in dark environment, only b colorimetric coordinate spectrophotometer was measured due to the yellow color of phenantroquinone. The samples were kept under two different conditions to be found under the UV light and natural environment outdoors. Colorimetric readings of the samples kept under UV light were made at the beginning (0 hours), 116 hours and at the end of 28 days, while the samples left in the open air were read at 0 hours and 28 days. Thus, the self-cleaning performances of the samples were determined. In addition, the dust obtained by grinding the samples taken from the surface of concrete samples containing 5% TiO₂ and 30% industrial waste was placed in the XRF measuring device and the chemical analysis was carried out and TiO₂ ratios on the surface were measured.

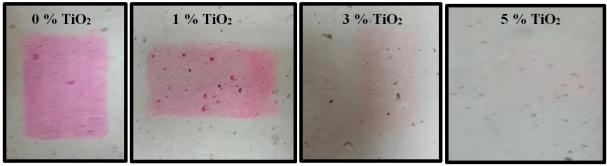


Figure 3. Exposing UV radiation and determining colorimetric parameters.

3. Experimental results and analysis

Slump, unit weight, ultrasound transition speed (UPV), compressive strength found in the results of experiments to determine the effects of industrial wastes and TiO₂ on the mechanical and physical properties of concrete are given in Table 5. When Table 5 is examined, as the percentage of use of FA and BFS in concrete increases, the slump values increase up to 67%, while the ST rate increases, the slump values decrease up to 37%. Due to the high water absorption capacity of ST, slump decreased due to the decreasing consistency. BFS and FA increased the process ability due to the lubrication effect, which caused the slump to increase. The slump increased when 5% TiO₂ was added to the samples without industrial additives. When the unit weight values of the samples are examined, unit weights decreased by 4.2% in case of industrial waste inclusion.

Table:	5. Pro	perties	of	SCC.
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T:O- 0/			FA,	%			BFS, %)			ST, %	ó	
	TiO ₂ , %	0	10	20	30	0	10	20	30	0	10	20	30
	0	130	150	150	180	130	160	180	170	150	130	120	110
Slump, mm	1	120	150	170	200	120	140	170	180	160	140	100	120
E E	3	150	140	170	170	150	140	180	170	150	120	140	100
	5	140	160	180	170	140	150	190	200	160	140	120	100
f,	0	2358	2336	2294	2262	2358	2331	2310	2278	2302	2275	2247	2255
igh 13	1	2342	2333	2297	2274	2342	2335	2311	2293	2315	2262	2251	2231
we g/n	3	2361	2321	2274	2269	2361	2322	2290	2295	2284	2305	2265	2248
Unit weight, kg/m³	5	2356	2306	2288	2281	2356	2330	2309	2304	2318	2286	2270	2261
	0	4.24	4.05	3.68	3.95	4.24	4.08	3.88	3.76	4.27	3.85	3.86	3.57
>, <	1	4.02	3.86	3.74	3.67	4.02	3.95	3.97	3.73	4.25	4.12	3.62	3.54
UPV, km/s	3	3.90	3.78	3.64	3.52	3.90	4.13	3.95	3.82	4.25	4.02	3.71	3.81
	5	4.14	3.72	3.61	3.66	4.14	4.03	3.86	3.68	4.37	3.94	3.70	3.79
ve	0	26.26	24.70	21.37	20.76	26.26	23.28	20.36	21.69	28.82	28.75	27.58	25.52
sssi gth,	1	25.57	22.54	22.52	19.79	25.57	23.33	21.65	20.86	30.14	28.53	24.03	25.24
ompressi strength, MPa	3	28.29	23.81	19.79	19.81	28.29	21.58	21.12	22.16	29.46	29.59	27.50	27.08
Compressive strength, MPa	5	26.58	24.76	19.97	20.12	26.58	23.72	20.28	21.58	31.07	27.57	26.60	26.72

Unit weights have decreased as industrial wastes with lower density compared to cement are used by replacing with cement. When UPV values are examined, UPV values decreased by 17% with the addition of industrial waste. UPV values were found to be lower as the lower specific surface areas of wastes compared to cement cause them to react more slowly and fill the voids more slowly. The addition of TiO_2 had no significant effect on the unit weight of the samples and the UPV. When the compressive strength values are analyzed in Figure 4, strengths decrease up to 25% in all samples have been observed due to the increase in the industrial waste percentage. It was observed that the compressive strength of the samples using ST was higher than the compressive strength of the samples using FA and BFS. The use of cement with a nominal compressive strength of 42.5 MPa in samples using FA and BFS, and the use of cement with a nominal compressive strength of 52.5 MPa in samples using ST can be shown as the reason for the change in concrete compressive strengths. The addition of TiO_2 had no significant effect on the unit weight, UPV and compressive strength of the samples.

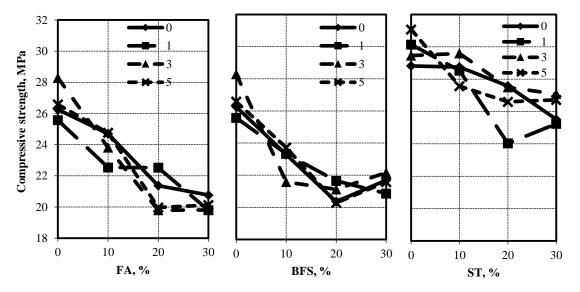


Figure 4. Compressive strength of concrete.

In order to determine the self-cleaning performance, the first color readings are taken as reference in samples whose surfaces are painted. Color readings were calculated by comparing the color readings made with samples kept under UV light with reference values. Time-dependent color fading samples containing FA using Rhodamine-B as contaminants is shown in Figure 5. When Figure 5 is examined, it is seen that the color fading is close to each other in the samples with TiO2 ratio below 5%. When the TiO₂ ratio was 5% in samples without FA, color fading increased approximately doubled. In the samples containing 5% TiO₂ and FA, the lightening increased up to three times. The most fading was observed as 58% in concretes containing 5% TiO2 and 20% FA. As a reason for this increase, it can be said that FA accelerates the reduction and oxidation reactions of photocatalysis, thereby breaking down the pollutant in greater amounts. When the color fading of the samples using BFS as industrial waste is evaluated, it is seen that the color fading increases in case of using 5% TiO₂. The highest color fading was observed in samples containing 5% TiO₂ and 10% BFS. It can be said that BFS has an active role in structural fragmentation of the pollutant in 10% usage, but this activity does not increase with the increase in BFS ratio. Because of white cement was used as a binder in samples produced using ST, it was easier to reflect the color during color readings. The fading of these samples is given in Figure 5. The fading of reference concretes exceeded 60% if 5% TiO₂ was used. The highest color fading was observed as 66% in concretes containing 5% TiO2 and 10% ST. It can be said that ST is not as effective as FA and BFS in photocatalysis reactions caused by TiO2. In the samples using phenantroquinone as pollutant, color fading was determined under artificial UV light in the indoor environment and without using artificial UV source in the open air.

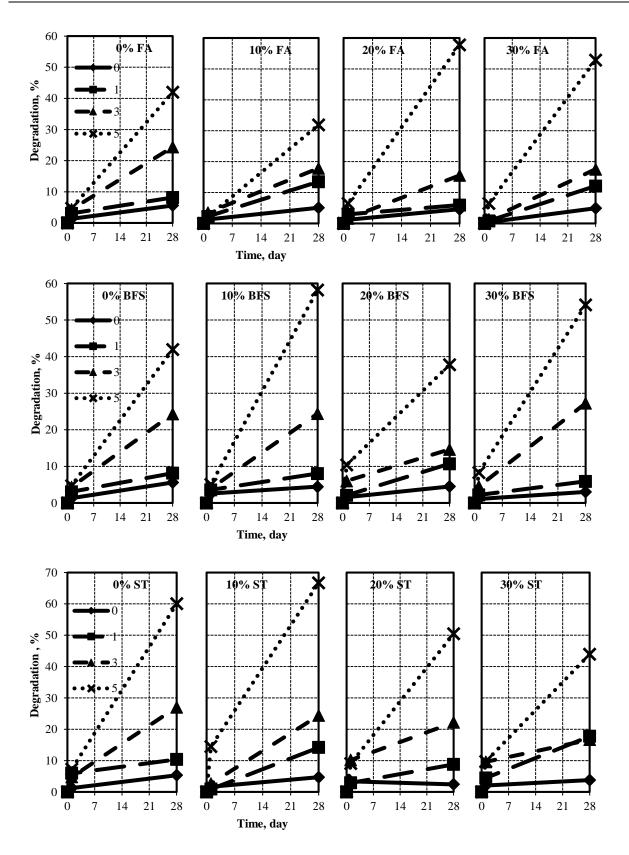


Figure 5. Photocatalytic degradation of Rhodamine-B of concrete.

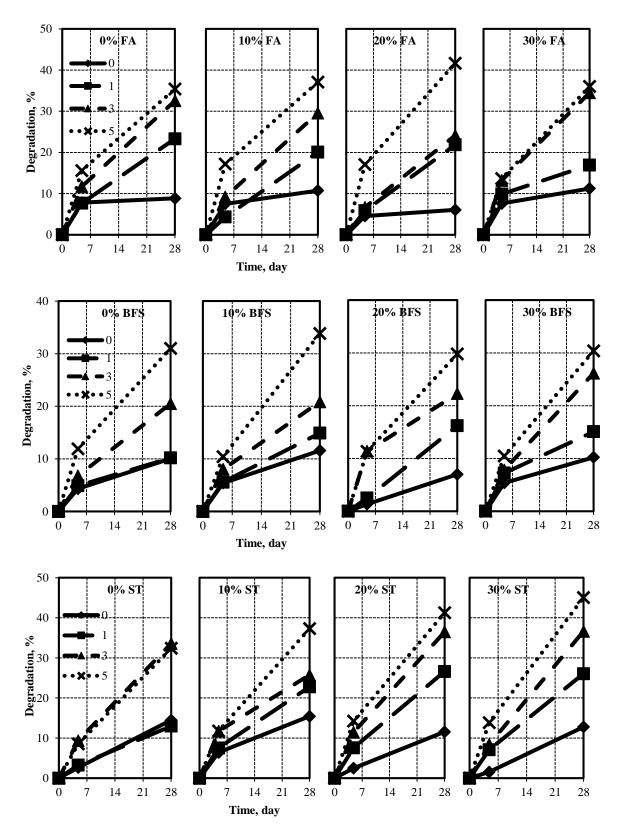


Figure 6. Photocatalytic degradation of Phenantroquinone of concrete.

Fading of the samples containing FA under artificial UV light in indoor environment is given in Figure 6. When Figure 6 is examined, the color fading increased approximately 2.5 times due to the increase of photocatalyst ratio in samples without FA. Maximum fadings were measured in samples using 5% TiO₂. In terms of color lightening, it can be said that the optimum FA usage rate in concrete is 20%. The fading in the experiments with Phenantroquinone has decreased by 20% compared to the fading in the experiments with Rhodamine. Accordingly, it can be said that Rhodamine-B is more easily broken down by photocatalysis and is more effective in determining the effect of the photocatalyst. Color fading of the samples using BFS is given in Figure 6. The highest color lightening was observed as 34% in concretes containing 5% TiO₂ and 10% BFS. It was observed that high rates of BFS use did not have a negative effect on photocatalysis reaction efficiency. As seen in Figure 6, more color fading values were obtained in the samples using sepiolite compared to other industrial waste samples, just like Rhodamine readings, in phenantroquinone readings. As the rate of use of sepiolite increased, the color fading values increased to 12%. Since the chemical structure of phenantroquinone is different compared to Rhodamine, 1% and 3% ratios of TiO₂ have also been effective in degradation phenantroquinone.

The color fading values of the samples using Phenantroquinone as an outdoor pollutant are shown in Figure 7. When Figure 7 is examined, maximum color fading values were obtained in samples using 5% TiO₂. The maximum fading value was 76% in concretes containing 5% TiO₂ and 20% ST. It has been observed that physical effects such as rain, wind in the open air are effective in removing the pollutants degradated by photocatalysis on the concrete surface and increasing the color fading values by around 30% to about 70% levels. Photocatalysis reactions in the open air did not take place at the desired level since it was not continuously exposed to UV light according to experiments with artificial UV source in the indoor environment. For this reason, in case of using TiO₂, there has been an increase in color fading up to 30% compared to reference samples without TiO₂.

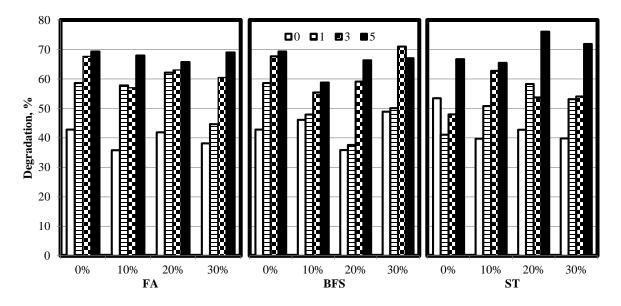


Figure 7. Photocatalytic degradation of Phenantroquinone of concrete under natural conditions.

The results of the XRF experiment carried out on samples reclaimed from concrete surfaces containing 5% TiO₂ and 30% industrial waste are given in Table 6. When Table 6 is examined, TiO₂ is observed at the surface of gray cement samples with FA and BFS additives at a rate of 1%. In ST-added white cement concrete samples, approximately 1.5% TiO₂ was observed on the surface. In experimental studies, TiO₂ was added at the rate of 5% of the binder. However, in the section taken from the concrete surface, not only the binder, but all the concrete including the aggregates were examined. Therefore, these values were expected to be below 5%. This result explains why color fading is higher in ST-cemented white cement samples.

Table 6. XRF of SCC.

Content. %	5% TiO ₂ + 30% FA	5% TiO ₂ + 30% BFS	5% TiO ₂ + 30% ST
Na ₂ O	0.2125	-	0.2439
MgO	2.2964	2.6241	5.7087
Al_2O_3	3.2473	3.3694	2.6841
SiO	9.7963	9.7496	11.3278
SO_3	0.7873	0.8489	1.2427
K_2O	0.2353	0.1498	0.1099
CaO	45.8425	47.1739	60.8962
TiO_2	0.9886	1.0192	1.5214
Fe ₂ O ₃	1.8305	0.9929	0.9606

The cement industry creates up to 5-8% of emissions of carbon dioxide in the world. Thus, greenhouse gas balance was affected badly (Zou et al., 2020; Azevedo et al., 2020b). Turkey is among the countries that influence the greenhouse gas balance with an annual production capacity of 100 million tons of cement (Akar and Canbaz, 2016). For this purpose, industrial wastes such as fly ash and blast furnace slag instead of cement are highly used in concrete (Gholampour and Ozbakkaloglu, 2017). The amount of industrial wastes is enough for evaluating in concrete production (Amaral et al., 2020). Reduction in cement ratio by using industrial waste in concrete, decreases the cement production and provides less carbon dioxide emissions (Azevedo et al., 2020c). In addition, utilization of industrial wastes in self-cleaning concrete production has extended the usage areas like green concrete production of these wastes.

One way to reduce the country's external dependence in energy production is to use low-calorie lignite coals in thermal power plants that cannot be utilized in other parts of the industry. Therefore, annual fly ash amounts are expected to increase more in the future. Currently, the annual production of fly ash from these power plants in Turkey, the average is about 13 million tons. In iron and steel production, blast furnace slag can be occurred up to 20% of the amount of steel. Iron and steel production in Turkey is the top ten in the world. In Turkey, the annual average of around 5.4 million tons of blast furnace slag is revealed. Storage of fly ash and blast furnace slag causes land resources pollution, groundwater pollution and air pollution in addition to the load it brings to thermal power plants and iron-steel plants.

4. Conclusions and comments

Increasing the FA and BFS ratio increased the slump values of the concrete mixtures, while the increase in the ST ratio caused a decrease in the slump values due to the fact that ST has a very high-water absorption capacity. As the density of the industrial wastes is less than the density of the cement, the unit weights of the concrete decreased as the amount of waste increased. Similarly, as the amount of waste increased, the UPV values and compressive strengths of the concrete decreased by 25%. While the addition of TiO₂ increased the slump values of the concrete, it had no significant effect on unit weight, UPV and compressive strength.

As a result of the Rhodamine B and Phenantroquinone test performed to determine the self-cleaning performance, it was observed that the best efficiency was obtained in samples containing 5% TiO₂. It has been observed that the self-cleaning performance of the samples containing waste material is also high. According to these results, TiO₂, which is used as a photocatalyst in photocatalysis reactions, can be mixed with FA, BFS, ST and used to increase its self-cleaning performance.

In the open environment, in the Phenantroquinone experiment without artificial UV source, effects such as rain and wind were very effective in removing the pollutant disintegrated by photocatalysis reactions on the concrete surface. This shows that the self-cleaning mechanism needs physical interventions such as water cleaning, except for photocatalysis reactions as examined in other studies (Xu et al., 2020). The results obtained in the Phenantroquinone experiment in open environment have obtained 30% more color fading rates.

As a result of study, it is recommended to use 5% TiO₂ as a photocatalyst for self-cleaning of concrete by photocatalysis reaction. It has been observed that in case of high amount of industrial wastes, it decreases concrete compressive strength. However, these rates can be recommended due to the positive effect of using waste materials in concrete at 20% FA, 10%

BFS, 10% ST rates both on self-cleaning performance and on the economic and environmental contribution of using these wastes in concrete.

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References

- Affam, A.C., & Chaudhuri, M. (2013). Degradation of pesticides chlorpyrifos, cypermethrin and chlorothalonil in aqueous solution by photocatalysis, Journal of Environmental Management, 130, 160-165. https://doi.org/10.1016/j.jenvman.2013.08.058
- Akar, C., & Canbaz M. (2016). Effect of molasses as an admixture on concrete durability. Journal of Cleaner Production 112, 2374-2380. https://doi.org/10.1016/j.jclepro.2015.09.081
- Amaral, L.F., Delaqua, G.C.G., Nicolite, M., Marvila, M.T., Azevedo, A.R.G., Alexandre J., Vieira, C.M.F., & Monteiro, S.N. (2020). Eco-friendly mortars with addition of ornamental stone waste A mathematical model approach for granulometric optimization, Journal of Cleaner Production, 248, 119283. https://doi.org/10.1016/j.jclepro.2019.119283
- Ângelo, J., Andrade, L., Madeira, L. M., & Mendes, A. (2013). An overview of photocatalysis phenomena applied to NOx abatement, Journal of Environmental Management, 129, 522-539. https://doi.org/10.1016/j.jenvman.2013.08.006
- Awadalla, A., Zain, M.F.M., Kadhum, A.A.H., & Abdalla, Z. (2011). Titanium dioxide as photocatalyses to create self-cleaning concrete and improve indoor air quality, International Journal of the Physical Sciences, 6, 6767-6774.
- Azevedo, A.R.G., Cecchin, D., Carmo, D.F., Silva, F.C., Campos, C.M.O., Shtrucka, T.G., Marvila, M.T., & Monteiro S.N. (2020a). Analysis of the compactness and properties of the hardened state of mortars with recycling of construction and demolition waste (CDW), Journal of Materials Research and Technology, 9(3), 5942-5952. https://doi.org/10.1016/j.jmrt.2020.03.122
- Azevedo, A.R.G., Marvila, M.T., Tayeh B.A., Cecchin, D., Pereira A.C., & Monteiro S.N. (2021). Technological performance of açaí natural fibre reinforced cement-based mortars, Journal of Building Engineering, 33, 101675. https://doi.org/10.1016/j.jobe.2020.101675
- Azevedo, A.R., Marvila, M.T., Zanelato, E.B., Alexandre, J., Xavier, G.C., & Cecchin, D. (2020b). Development of mortar for laying and coating with pineapple fibers, Revista Brasileira de Engenharia Agrícola e Ambiental, 24, 187-193. http://dx.doi.org/10.1590/1807-1929/agriambi.v24n3p187-193
- Azevedo, A.R.G., Klyuev, S., Marvila, M.T., Vatin, N., Alfimova, N., Lima, T.E.S., Fediuk R., & Olisov, A. (2020c). Investigation of the Potential Use of Curauá Fiber for Reinforcing Mortars, Fibers, 8,69. https://doi:10.3390/fib8110069
- Calia, A., Lettieri, M., Masieri, M., Pal, S., Licciulli, A., & Arima, V. (2017). Limestones coated with photocatalytic TiO2 to enhance building surface with self-cleaning and depolluting abilities. Journal of Cleaner Production, 165, 1036-1047. https://doi.org/10.1016/j.jclepro.2017.07.193
- Chang, J.A., Vithal, M., Baek, I.C., & Seok, S. (2009). Morphological and phase evolution of TiO2 nanocrystals prepared from peroxotitanate complex aqueous solution: Influence of acetic acid, Journal of Solid State Chemistry, 182, 749–756. https://doi.org/10.1016/j.jssc.2008.12.024
- Chen, J., Kou, S., & Poon, C. (2011). Photocatalytic cement-based materials: Comparison of nitrogen oxides and toluene removal potentials and evaluation of self-cleaning performance, 46, 1827-1833. https://doi.org/10.1016/j.buildenv.2011.03.004
- Chen, J., & Poon, C. (2009). Photocatalytic construction and building metarials: From fundamental to applications, Building and Environment, 44, 1899-1906. https://doi.org/10.1016/j.buildenv.2009.01.002
- Costa, A. L., Ortelli, S., Blosi, M., Albonetti, S., & Vaccari, A. (2013). TiO2 based photocatalytic coatings: From nanostructure to functional properties, Chemical Engineering Journal, 225, 880-886. https://doi.org/10.1016/j.cej.2013.04.037
- Delnavaz M., Ayati B., Ganjidoust H., & Sanjabi S. (2015). Application of concrete surfaces as novel substrate for immobilization of TiO2 nano powder in photocatalytic treatment of phenolic water, Journal of Environmental Health Science & Engineering, 13, 1-10. https://doi.org/10.1186/s40201-015-0214-y
- Ferella, F. (2019). A review on management and recycling of spent selective catalytic reduction catalysts. Journal of Cleaner Production: 118990. https://doi.org/10.1016/j.jclepro.2019.118990

- Fiore, A., Marano, G.C., Monaco, P., & Morbi, A. (2013). Preliminary experimental study on the effects of surface-applied photocatalytic products on the durability of reinforced concrete, Construction and Building Metarials, 48,137-143. https://doi.org/10.1016/j.conbuildmat.2013.06.058
- Folli, A., Jakobsen, U.H., Guerrini, G.L., & Macphee, D.E. (2009). Rhodamine-B discolouration on TiO2 in the cement environment: A look at fundamental aspects of the self-cleaning effect in concretes, Journal of Advanced Oxidation Technologies, 12, 126-133. https://doi.org/10.1515/jaots-2009-0116
- Folli, A., & Macphee, D.E. (2010). Photocatalytic cement: influence of TiO2 particle size on photocatalytic performances, 8th fib International PhD Symposium in Civil Engineering, 1-6.
- Gholampour, A., & Ozbakkaloglu T. (2017). Performance of sustainable concretes containing very high volume Class-F fly ash and ground granulated blast furnace slag. Journal of Cleaner Production 162, 1407-1417. https://doi.org/10.1016/j.jclepro.2017.06.087
- Guo, M. Z., Maury-Ramirez, A., & Poon, C. S. (2016). Self-cleaning ability of titanium dioxide clear paint coated architectural mortar and its potential in field application. Journal of cleaner production, 112, 3583-3588. https://doi.org/10.1016/j.jclepro.2015.10.079
- Gürbüz, M., Solaş, A., Küçük, A., Göktaş, A., & Doğan, A. (2009). The Production of Environmental Friendly Photocatalytic and Antimicrobial Ceramic Materials by Nanotechnology, Afyon Kocatepe University Journal of Science and Engineering, special issue, 217-221.
- Hanus, M.J., & Harris, A.T. (2013). Nanotechnology innovations for the construction industry, Progress in Materials Science, 58, 1056-1102. https://doi.org/10.1016/j.pmatsci.2013.04.001
- He, B., Gao, Y., Qu, L., Duan, K., Zhou, W., & Pei, G. (2019). Characteristics analysis of self-luminescent cement-based composite materials with self-cleaning effect." Journal of Cleaner Production 225, 1169-1183. https://doi.org/10.1016/j.jclepro.2019.03.291
- Hunger, M., & Brouwers, H.J.H. (2009). Self-cleaning surfaces as an innovative potential for sustainable concrete, Excellence in Concrete Construction through Innovation 545-552.
- Hüsken, G., Hunger, M., & Brouwers, H.J.H. (2009). Experimental study of photocatalytic concrete products for air purification, Building and Environment, 44, 2463-2474. https://doi.org/10.1016/j.buildenv.2009.04.010
- Janus, M., Zatorska, J., Czyewski, A., Bubacz, K., Nejman, E.K, & Morawski A.W. (2015). Self-cleaning properties of cement plates loaded with N, C-modified TiO2 photocatalysts, Applied Surface Science, 330, 200-206. https://doi.org/10.1016/j.apsusc.2014.12.113
- Krishnan, P., Zhang, M.H., Yu, L., & Feng, H. (2013). Photocatalytic degradation of particulate pollutants and self-cleaning performance of TiO2-containing silicate coating and mortar, Constructions and Buildings Materiels, 44, 309-316. https://doi.org/10.1016/j.conbuildmat.2013.03.009
- Lucas, S.S., Ferreira, V.M., & Barroso de Aguiar, J.L. (2013). Incorporation of titanium dioxide nanoparticles in mortars Influence of microstructure in the hardened state properties and photocatalytic activity, Cement and Concrete Research, 43, 112-120. https://doi.org/10.1016/j.cemconres.2012.09.007
- Luna, M., Gatica, J. M., Vidal, H., & Mosquera, M. J. (2020). Use of Au/N-TiO2/SiO2 photocatalysts in building materials with NO depolluting activity. Journal of Cleaner Production 243, 118633. https://doi.org/10.1016/j.jclepro.2019.118633
- Melo, J.V.S., & Triches, G. (2012). Evaluation of the influence of environmental conditions on the efficiency of photocatalytic coatings in the degradation of nitrogen oxides (NOx), Building and Environment, 49, 117-123. https://doi.org/10.1016/j.buildenv.2011.09.016
- Mendoza, C., Valle, A., Castellote, M., Bahamonde, A., & Faraldos, M. (2015). TiO2 and TiO2- SiO2 coated cement: Comparison of mechanic and photocatalytic properties, Applied Catalysis B: Environmental, 178, 155-164. https://doi.org/10.1016/j.apcatb.2014.09.079
- Nakata, K., & Fujishima, A. (2012). TiO2 photocatalysis: Design and applications, Journal of Photochemistry and Photobiology C: Photochemistry Reviews, 13, 169-189. https://doi.org/10.1016/j.jphotochemrev.2012.06.001
- Pozo-Antonio, J. S., & Dionísio, A. (2017). Self-cleaning property of mortars with TiO2 addition using real diesel exhaust soot. Journal of Cleaner Production, 161, 850-859. https://doi.org/10.1016/j.jclepro.2017.05.202
- Ramirez, A.M., Demeestere, K., & Belie, N.D. (2012). Photocatalytic activity of titanium dioxide nanoparticle coatings applied on autoclaved aerated concrete: Effect of weathearing on coathing physical characteristics and gaseous toluene removal, Journal of Hazardous Materials, 211, 218-225. https://doi.org/10.1016/j.jhazmat.2011.12.037
- Ruot, B., Plassais, A., Olive, F., Guillot, L., & Bonafous, L. (2009). TiO2-containing cement pastes and mortars: Measurements of the photocatalytic efficiency using a Rhodamine B-based colourimetric test, Solar Energy, 83, 1794-1801. https://doi.org/10.1016/j.solener.2009.05.017
- Shen, W., Zhang, C., Li, Q., Zhang, W., Cao, L., & Ye, J. (2015). Preparation of titanium dioxide nano particle modified photocatalytic self-cleaning concrete. Journal of cleaner production, 87, 762-765. https://doi.org/10.1016/j.jclepro.2014.10.014
- Sikora, P., Horszczaruk, E., & Rucinska T. (2015). The effect of nanosilica and titanium dioxide on the mechanical and self-cleaning properties of wasteglass cement mortar, Procedia Engineering, 108, 146-153. https://doi.org/10.1016/j.proeng.2015.06.130
- Silva, R. V., De Brito, J., Lynn, C. J., & Dhir, R. K. (2017). Use of municipal solid waste incineration bottom ashes in alkali-activated materials, ceramics and granular applications: A review. Waste Management, 68, 207-220. https://doi.org/10.1016/j.wasman.2017.06.043
- Stamate, M., & Lazar, G. (2007). Application of titanium dioxide photocatalysis to create self-cleaning materials, Romanian Technical Sciences Academy, 3, 280-285.

- Topcu, I. B., & Canbaz, M. (2007). Effect of different fibers on the mechanical properties of concrete containing fly ash. Construction and Building Materials, 21(7), 1486-1491. https://doi.org/10.1016/j.conbuildmat.2006.06.026
- Torgal, F.P., & Jalali, S. (2011). Nanotechnology: Advantages and drawbacks in the field of construction and building metarials, Construction and Building Metarials, 25, 582-590. https://doi.org/10.1016/j.conbuildmat.2010.07.009
- UNI 11259, (2008). Determination of the photocatalytic activity of hydraulic binders rodammina test method.
- Ünal S. (2015). Self-Cleaning Concretes Containing Industrial Waste, MSc Thesis, Eskişehir Osmangazi University, Institute of Science, 124 p., Turkey.
- Vasilache, T., Lazar, I., Stamate, M., Nedeff, V., & Lazar, G. (2013). Possible environmental risks of photocatalysis used for water and air depollution case of phosgene generation, APCBEE Procedia 5, 181 185. https://doi.org/10.1016/j.apcbee.2013.05.032
- Xu, Y., Jin, R., Hu, L., Li, B., Chen, W., Shen, J., Wu P., & Fang, J. (2020). Studying the mix design and investigating the photocatalytic performance of pervious concrete containing TiO2-Soaked recycled aggregates. Journal of Cleaner Production 248, 119281. https://doi.org/10.1016/j.jcle-pro.2019.119281
- Yin, K., Ahamed, A., & Lisak, G. (2018). Environmental perspectives of recycling various combustion ashes in cement production—A review. Waste Management, 78, 401-416. https://doi.org/10.1016/j.wasman.2018.06.012
- Yüksel, F.Ş.K., & Karagüler, M. (2011). Self-cleaning concrete, Proceeding of Concrete 2011 Congress, 470-480.
- Zou, F., Hu, C., Wang, F., Ruan, Y., & Hu, S. (2020). Enhancement of early-age strength of the high content fly ash blended cement paste by sodium sulfate and C–S–H seeds towards a greener binder. Journal of Cleaner Production 244, 118566. https://doi.org/10.1016/j.jclepro.2019.118566.

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