Chapter 22
An Assessment of Mechanical Properties on Self-Cleaning Concrete Incorporating Rutile Titanium Dioxide

Mohd Syahrul Hisyam Mohd Sani, Fadhluhartini Muftah, and Nazree Ahmad

Abstract Concrete is made of cement, sand, gravel and water to produce an applicable paste, which is continuously hardened over time. There was a lot of problems that occurred in concrete when the strength lost its integrity subjected to load and also a dirty concrete surface due to aggressive air pollution in crowded cities, industrial areas and/or marine structured buildings. Self-cleaning concrete using rutile titanium dioxide (TiO_2) as an additive known as nanomaterial was proposed for this study. The utilisation of photocatalytic materials in concrete was able to solve the problem and also assisted to reduce and degrade air pollution under ultraviolet radiation. The main objective of this study was to determine the mechanical properties of self-cleaning concrete using rutile TiO_2. TiO_2 with percentages of 0.50, 1.00, 1.50, 2.00, 2.50, 3.00 and 3.50% of the total weight of the cement was used. There were two parts in the experimental activity, which included the physical and chemical of the TiO_2 and the mechanical properties of the self-cleaning concrete. From the results, the self-cleaning concrete with 0.50 and 1.00% was reported to have a compressive strength value more than the control mix, approximately 0, 1.16 and 6.0%.

Keywords Self-cleaning concrete · Mechanical properties · Titanium dioxide · Photocatalytic action

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22.1 Introduction

Concrete is a building composite material, which is used in construction activities that consists of cement, gravel, sand and water, and added with some admixtures in required proportions for modifying and updating purposes. The additive or additional material used in the concrete paste is depended on the application and solving of the problem's purposes. Concrete is considered throughout the years because it is categorised as the cheapest material in construction, for example, for onshore or offshore buildings, pavements, tunnels, bridges, etc. Nowadays, concrete is studied to produce better strength, durability, workability, flexibility and capability in solving environmental problems. Spiesz et al. [1] reported that concrete was popular due to its mechanical properties, durability, flexibility, architectural options and fairly low price. Therefore, the concrete's ingredients were replaced or added with waste material or chemical substance to obtain a better result and minimising the problems.

The improvement of concrete, especially in the strength, which is depended on the composition and quality of ingredients, is an important way to resist or sustain the load. Recently, the study of improving the strength of concrete was by adding nanoparticles such as titanium dioxide (TiO_2), aluminium oxide (Al_2O_3), and zinc oxide (ZnO). Normally, nanoparticles used in concrete were responsible to fill the gap between the concrete ingredients, to produce the solid condition of the concrete and to promote the strength.

Dikkar et al. [2] reported that TiO_2 had become increasingly popular in recent years and frequently used in food and other consumer goods as an additive. There were four million tons of TiO_2 used in consumer goods, for instance papers, medicine, sunblock cream, toothpaste, paints and inks [3]. Elia et al. [3] reported that TiO_2 was divided into three major forms which were known as anatase, rutile and brookite. TiO_2 was added to the concrete or replaced the cement for exhibiting a self-cleaning property due to photocatalyst actions with the presence of TiO_2. A previous study determined the mechanical properties of self-cleaning concrete by replacing or substituting the cement with TiO_2 [4, 5] and TiO_2 as an additive [6].

Photocatalyst actions were activated by utilising direct UV radiation or direct sunlight and normally could not affect the concrete properties, especially on the strength and durability. Concrete with self-cleaning property is known as self-cleaning concrete or is recognised as photocatalytic concrete [7] or air-purifying concrete [8]. TiO_2 is able to decompose harmful gaseous when the solid body is exposed to sunlight.

The concrete lost its structural integrity when the concrete was observed to have cracked in the shortest time of application and easily broken. Additionally, the concrete was exposed to aggressive environmental problems, especially in crowded cities, developing countries and industrial areas, which was prone to pollutant agents such as transportation, factories and tobacco smoke. Chen et al. [9] mentioned that the air pollution from traffic vehicle's exhaust or vehicle combustion affected the economic development, the environment such as acid rain, ozone depletion and greenhouse effect, and public health such as lung diseases, cardiovascular diseases and respiratory problems. Elia et al. [3] and Odedra et al. [10] stated that the most hazardous air pollutants were recorded such as carbon monoxide, nitrogen oxides (NO_x), lead, sulphur dioxide and volatile organic compounds (VOC). Pollution could contribute a negative impact on human beings, other living organisms and also the concrete. Furthermore, the concrete surface became darker in colour and needed high maintenance cost and cleaning process. Therefore, the study of concrete with additional TiO_2 is to produce a clean concrete surface, reduce the smoke and harmful gases, reduce pollution and improve the strength of the concrete. The pollutants from organic and inorganic sources and particulate matter have the potential to speed up the degradation of concrete in buildings and create significant changes in the material's aesthetic and physical qualities [11].

Several researchers tried to use other materials as replacements or additives, whereby chemical actions were used to produce a better compressive strength. Shchelokova et al. [12] studied the utilisation of an additive on SiO_2-TiO_2 oxides in cement for improving the compressive strength of concrete and parallel with the capability of self-cleaning property. Krishnan et al. [13] studied the effect of compressive strength using the metakaolin-based geopolymer matrix and reported that the result increased with an increasing percentage of TiO_2. Gonzalez-Sanchez et al. [14] used nanosilica, which is known as pozzolanic mineral admixtures and TiO_2 in lime mortar to improve the compressive strength and proposed the self-cleaning property. Satyanarayana and Padmapriya [15] studied the properties of the self-cleaning concrete made by mixing manufactured sand as a sand replacement, palm oil fuel ash as cement replacement and TiO_2. Xu et al. [16] reported that the recycled fine aggregate with a range of 0.16–5 mm and recycled coarse aggregate with a range of 5–25 mm were used in the production of the self-cleaning concrete.

The self-cleaning concrete had created an eco-friendly environment, cleaned the indoor air pollutants inside the concrete and reduced harmful gases from entering the concrete by absorbing ultraviolet radiation [8]. The objective of this study was to determine the mechanical properties of the self-cleaning concrete with the addition of rutile TiO_2.

22.2 Methodology

The study was divided into two parts, which comprised the chemical and physical properties of the TiO_2 and the mechanical properties of the self-cleaning concrete. The physical and chemical properties of TiO_2 were compared with the cement used in the self-cleaning concrete. The cement that was used in the study was the composite Portland cement. The cement and TiO_2 are illustrated in Fig. 22.1. The grade M25 of self-cleaning concrete was prepared with TiO_2 of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5%. A superplasticiser was not used in the study. The specimen of the self-cleaning concrete was with the percentage of TiO_2 on the weight of cement. The proportions of TiO_2 referred to a study by Sorathiya et al. [17] with 0.5, 0.75, 1.0, 1.25 and 1.5% from the weight of cement. The control mix without TiO_2 (0%) was prepared

Fig. 22.1 Example of the **a** cement and **b** rutile TiO_2

for comparing and verifying the results of the mechanical properties. There were a total of 24 specimens, whereby every percentage of TiO_2 had three specimens. The workability of the self-cleaning concrete was tested and observed for fresh conditions. For hardened conditions, the compressive strength of the cubes (100 × 100 × 100 mm) for seven days, 28 days and 60 days was conducted and determined. The compression machine of 2000 kN capacity determined the compressive strength.

22.3 Results and Discussion

The results and discussion of this study were divided into physical and chemical properties of TiO_2 compared with cement, workability test of fresh self-cleaning concrete and mechanical properties of self-cleaning concrete with different percentages of TiO_2.

22.3.1 Physical Properties

The physical properties of TiO_2 were observed and tested by comparing them with the cement and other previous studies. Table 22.1 tabulates the physical properties of TiO_2 and cement. The result of the physical properties was compared with anatase TiO_2. It showed that the density of rutile TiO_2 was less than cement, but more than anatase TiO_2 liquid-based. Anatase TiO_2 was classified as the most photoactive when compared with rutile, which lowered thermal stability and was inexpensive [18]. Sakthivel et al. [19] reported that the anatase TiO_2 and rutile TiO_2 obtained a tetragonal crystal structure, which was appropriate for photocatalytic action.

Table 22.1 Physical properties of TiO_2 and cement

Physical properties	TiO_2	Cement	TiO_2 [1]
Particles size	1.0–2.0 µm	0.1–250 µm	40–300 nm
Colour and appearance	White powder	Grey powder	Milky liquid
Density (g/cm^3)	3.15	4.23	1.43
Type	Rutile	Composite Portland cement	Anatase

22.3.2 Chemical Properties

The chemical properties and surface morphology analysis of cement and TiO_2 were determined using a scanning electron microscope (SEM). Figures 22.2 and 22.3 illustrate the surface morphology of cement and TiO_2 using the SEM images with 500x and 5000x magnification, respectively. From the images, the TiO_2 showed a finer and clearly solid surface, while the cement illustrated consisted of more pores. It was shown that the TiO_2 formed the denser particles, and it was proven that TiO_2 was the finest material and categorised as a nanomaterial group. Therefore, TiO_2 is

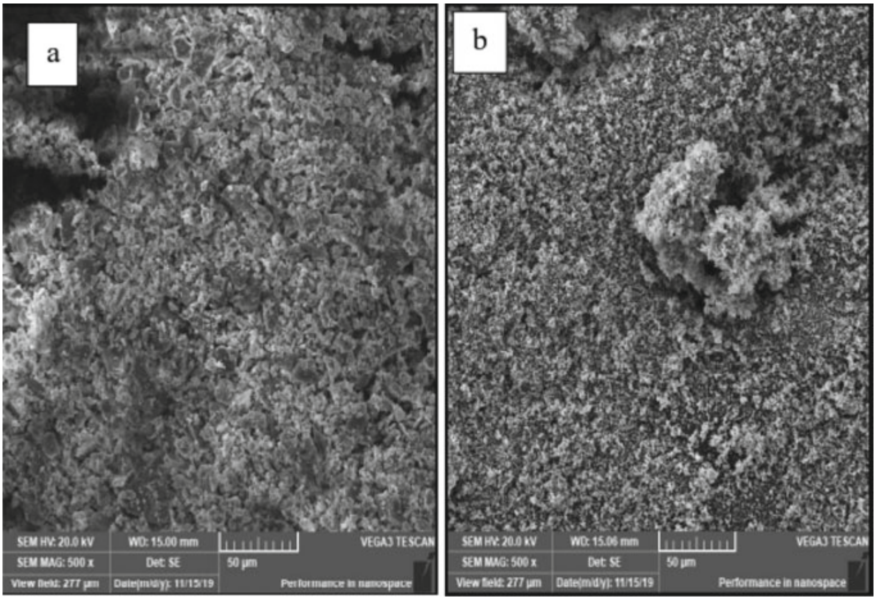

Fig. 22.2 Surface morphology of with 500x magnification of **a** normal cement and **b** rutile TiO_2

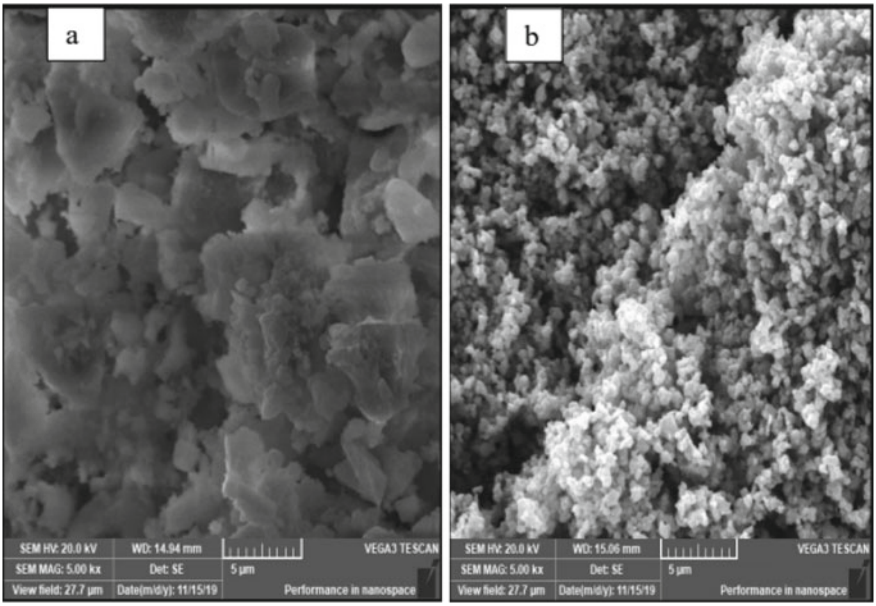

Fig. 22.3 Surface morphology of with 5000x magnification of **a** normal cement and **b** rutile TiO_2

appropriate to be added into the concrete to blend with the cement for producing a compact condition without small air void to produce a stronger concrete.

The energy dispersive X-ray spectroscopy (EDS) technique was used to measure the X-rays emitted from the specimen using an electron beam to determine the elemental composition of the volume. Figure 22.4a and b illustrates the EDS layered electron image and EDS spectrum of cement and TiO_2, respectively. The cement EDS layered electron image was more colourful when compared to TiO_2, due to the content of several elements in it. Besides, the layer of an electron in cement showed to be more compact rather than TiO_2. Table 22.2 illustrates the chemical composition of cement and TiO_2. From Table 22.2, the cement consisted of the highest percentage with the highest peak of calcium (Ca), while titania showed the highest percentage in TiO_2. The percentage difference between rutile TiO_2 with cement and nitrogen-doped TiO_2-SiO_2 for major chemical composition was 1.60% and 10.85%, respectively, for oxygen.

22.3.3 *Workability Test*

The workability test of fresh concrete was defined by determining the height of the slump. Figure 22.5 represents the result of the height of the slump for different percentages of TiO_2. It shows that the workability of self-cleaning concrete of the

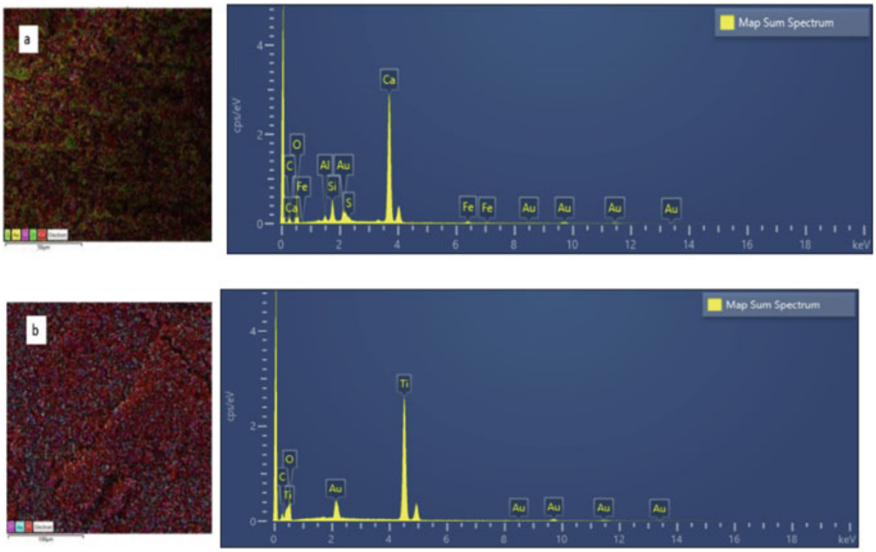

Fig. 22.4 **a** EDS layered electron image and spectrum of cement and **b** the EDS layered electron image and spectrum of rutile TiO_2

Table 22.2 Chemical composition of cement and TiO_2

Chemical composition	Weight of element (%)		
	Cement	TiO_2	Nitrogen-doped TiO_2-SiO_2 [20]
Oxygen (O)	38.60	37.98	42.60
Calcium (Ca)	37.98	–	6.90
Titanium (Ti)	–	38.60	14.42
Aurum (Au)	7.80	3.25	–
Carbon (C)	9.44	9.44	13.10
Silicon (Si)	3.25	–	17.40
Aluminium (Al)	1.04	–	1.30
Iron (Fe)	1.08	–	–
Sulphur (S)	0.81	–	–

control mix (0%) was the same as the specimen with 0.50 and 1.50%. The highest workability amongst the specimens was 1.00% and the lowest workability was 3.50%. The percentage difference between the control mix of 0% with the highest and lowest workability was around 28.57% and 70%, respectively. The slump height was decreased when compared with the percentage of TiO_2 of 1.00% to roughly 28.57% of 1.50%, 50% of 2.00%, 64.3% of 2.50%, 71.4% of 3.00% and 78.6% of 3.50%. Thus, the workability of the concrete by referring to the slump height was decreased when it passed 1.00% of TiO_2. From the results, TiO_2 was reported to have

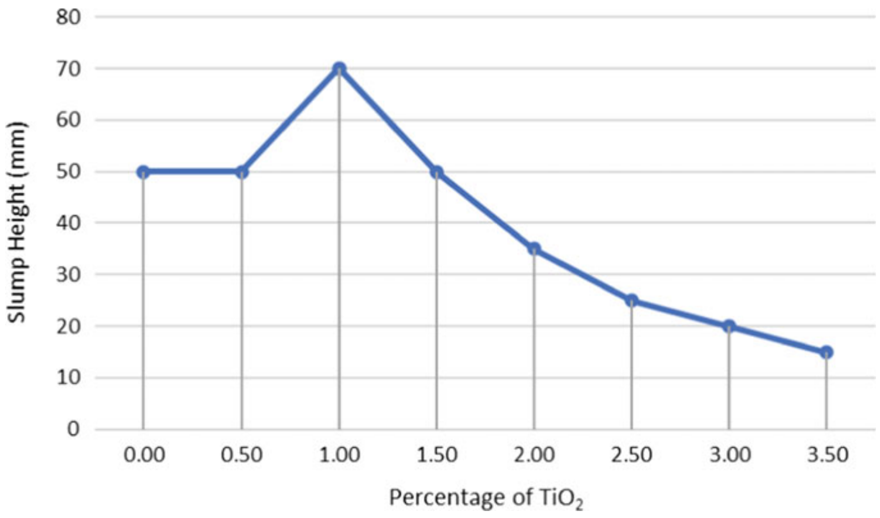

Fig. 22.5 Height of slump with different of the percentage of TiO_2

high water absorption in concrete and should be added with the superplasticiser for maintaining the water content. The result of a study by Sorathiya et al. [17] showed that the slump value was decreased with the increase in the percentage of TiO_2 and the slump value was conservative at 0.5% and 1.0%.

22.3.4 Compression Strength

The compressive strength of self-cleaning concrete with different TiO_2 is shown in Table 22.3 and Fig. 22.6. The highest value at 28 days of compressive strength was 28.38 MPa for 1.00% and the lowest value of compressive strength was 20.44 MPa

Table 22.3 Result of compressive strength for 7, 28 and 60 days

Specimen	Compressive strength (MPa)		
	7 days	28 days	60 days
0	18.94	26.68	31.97
0.50%	19.15	26.99	32.90
1.00%	20.12	28.38	35.75
1.50%	17.77	24.68	29.00
2.00%	16.00	22.16	27.80
2.50%	15.67	21.79	24.70
3.00%	14.72	20.44	30.60
3.50%	15.95	22.00	33.80

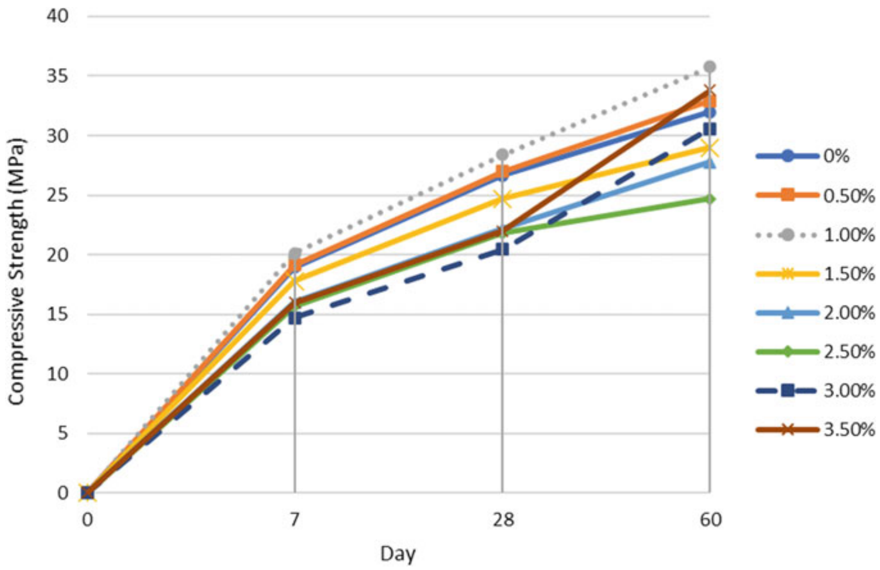

Fig. 22.6 Compressive strength of the self-cleaning concrete

for 3.00%. The percentage difference between the control mix with other specimens were 0.50, 1.00, 1.50, 2.00, 2.50, 3.00 and 3.50% at 28 days, which was reported to obtain 1.17, 6.00, 7.48, 16.93, 18.30, 23.36 and 17.53%, respectively. Two specimens were noted to have a compressive strength value of more than the control mix (0%); a specimen of 0.50 and 1.00% of TiO_2. The compressive strength was increased with the increase in the percentage of TiO_2 from 0.50 to 1.00%, but the compressive strength decreased when the percentage of TiO_2 increased after 1.00% of TiO_2, as shown in Fig. 22.7. Figure 22.7 showed the complete compressive strength with different percentages of TiO_2 for 7, 28 and 60 days. Figure 22.8 illustrated the failure mode of the specimen with 1.0% of TiO_2.

The result of the compressive strength was proven by Dikkar et al. [2] who reported that the strength with 0.5% of TiO_2 was increased, but reduced when the TiO_2 increased to 1.0–1.5%. The reduction of the compressive strength of self-cleaning concrete with 1.0% of TiO_2 from the study of Dikkar et al. [2] was reported to be conservative.

22.4 Conclusion

A series of experimental works was conducted to determine the chemical, physical and mechanical properties of TiO_2 and the self-cleaning concrete with different percentages of TiO_2. From the observation and results, some conclusion could be drawn as follows:

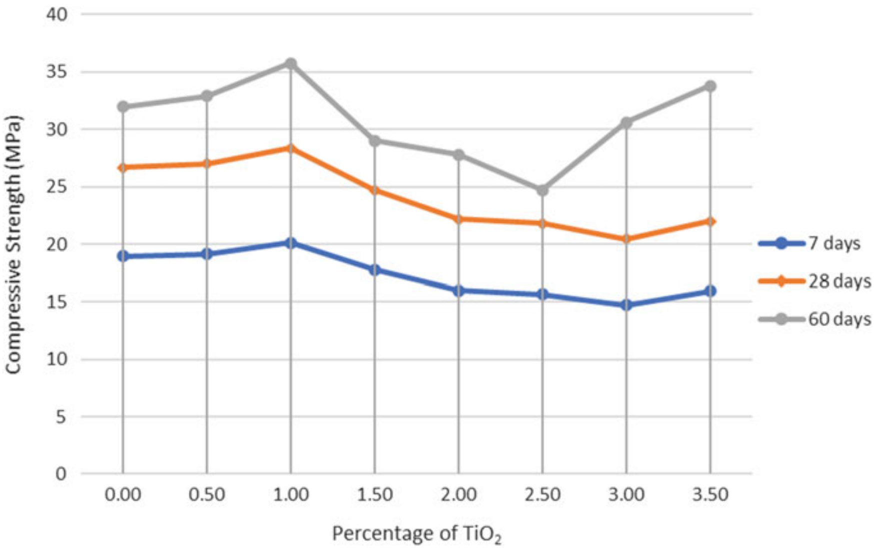

Fig. 22.7 Relationship of the percentage of TiO_2 and compressive strength of self-cleaning concrete

Fig. 22.8 Failure mode of the specimen with 1.0% of TiO_2

1. The workability of specimens was increased from 0% to 1.00% of TiO_2, but the workability of specimens decreased when the percentage of TiO_2 increased, exceeding 1.00%.
2. The compressive strength of self-cleaning concrete increased when the percentage of TiO_2 increased between 0.50 and 1.00%. However, the compressive strength of the self-cleaning concrete decreased with the increase in percentage of TiO_2 from 1.50 to 3.50%.
3. The specimen of self-cleaning concrete with 1.00% of TiO_2 showed the best results amongst the specimens for workability and compressive strength when compared to the control mix.

Further research activities, specifically the experimental, are recommended to obtain the best solution for workability and strength by adding the superplasticiser into the self-cleaning concrete. Additionally, the study of the self-cleaning concrete with an additional percentage of the TiO_2 of up to 10.00% or the study of the self-cleaning concrete with replacement of cement by the TiO_2 should be done to obtain a good relationship.

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