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The Effect of Mineral Pigments on Mechanical Properties of Concrete

Amr Maher El Nemr*, Maha Ahmed Shawky, Mahmoud El Khafif

Civil Engineering Program, German University in Cairo (GUC), Cairo, Egypt
E-mail: amr.elnemr@guc.edu.eg (Corresponding author); maha.shawky@guc.edu.eg; mahmoud.elkhafif@guc.edu.eg

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Abstract: Pigmented concrete exhibits artesian properties in addition to ordinary concrete properties, explicitly high strength, excellent durability, and weather resistance. However, the influence of several parameters that affect the characteristics of colored concrete should be studied; extensively. In this paper, the impact of the w/b (water/binder) ratio using color pigments on the mechanical properties such as compressive and flexural strengths of colored cement mortar prisms and cubes experimentally investigated. The experimental program included 21 mixes with six cubes and three flexural prisms specimens for assessing compressive and flexural strength, respectively. The blends included different water/binder ratios with values of 0.4, 0.5, and 0.6, in addition to several color pigments as a partial replacement of cement. The percentage of replacements altered between 0, 2.5%, 5% and 7.5% with two different shades of pigments consisting of red iron and green chromium oxide. Based on the experimental results, empirical expressions were generated based on Abram's law to assess the relationship between the compressive strength of colored concrete and w/b ratio. The results revealed that the compressive and flexural strength of colored concrete is influenced by w/b ratio and partially replacement percentage of cement by color pigment not proportionally direct. Furthermore, the shade of pigments also has a different impact as well.
Keywords: Pigmented concrete; Water/binder ratio; Mechanical properties.

1. Introduction

Colored concrete was developed during the 1950s, while adding synthetic iron oxide, a byproduct waste from chemical manufacturing, to the gray concrete mix. Great designs and enhanced exterior, interior, and finishing of buildings or structures can achieve by adding colored powders to conventional concrete. No paintings required, only different shades of pigments and cement to achieve the required concrete color [1]. As everyday construction demand increases, colored concrete became of high demand in contemporary architecture, mainly because of the significant evolution of its shape, texture, and color options. Consequently, the produced concrete must fulfill not only the physical and mechanical characteristics of the ordinary non-pigmented concrete, but also satisfy the visual aesthetic concerns, which affect the surface quality. Furthermore, it should sustain durability and environmental exposure or condition [2, 3].

Historically, in 1915, Lynn Mason Scofield, who is an engineer and inventor in Chicago, presented the first effective products for coloring, staining, and strengthening concrete through a leading company for manufacturing of colored concrete. Different products were established, including color hardeners, integral colors, sealers, and chemical stains, creating a broad spectrum of colored concrete [4]. On the other hand, several characteristics obtained by using the right pigment admixtures. Colored concrete can attain strong structural capabilities, remain maintenance-free, and achieve a long-lasting and durable material appearance [3, 5]. However, due to negative environmental impact of cement, the trend is to replace partially of any materials that could be working as supplementary cementitious materials without influencing the mechanical properties of concrete produced [6 – 8].

The mechanical properties of concrete are usually affected by several parameters. The most critical sets are the water-cement ratio, followed by the cement content, then the aggregate type, and the compaction degree. The amount of admixtures also has a significant influence on concrete when used. Accordingly, it expected that the pigments' admixtures impact the mechanical properties of concrete. Dosage and chemical composition of coloring admixtures are usually the critical variables in the study of colored concretes. Commercially, the handbook and guideline manual [9] for pigment admixtures limited the ratio of pigments to 5% of the cement weight. The allowance percentage (5%) limited due to the reduction in strength capabilities of mortar or concrete if larger quantities added [10].

As the water-binder ratio increases, the workability of concrete increases. This workability eases the concrete placement and its flowability, yet it reduces the strength. Several researchers investigated colored concrete through an experimental program consisting of several mixes with various pigment dosages [9 - 12]. Few researchers [9, 12] observed that using pigments for producing colored concrete does not significantly influence the mechanical properties of the hardened concrete. The authors concluded that the mechanical properties of colored concrete affected by the type of pigments used (i.e., Metal oxides used), which in turn translated to the pigment composition. The composition is not the only factor; however, the authors observed that the dosage and manufacturing process also imply the mechanical properties of colored concrete.

A primary factor for the strength of concrete is the strength of the cement paste. In other words, the strength of paste increases with cement content and decreases with rising air and water content. Abram's law provides a nonlinear relationship between the water-cement ratio and the compressive strength of concrete. The equation based on the power model, which assumes an inverse relationship between compressive strength and the water-cement ratio at a given age and average temperature [13, 14].

Rao [15] validated the applicability of Abram's law equation at any age for water-cement ratio ranging from 0.27 to 0.5. Other researchers [16, 17] developed empirical model expressions based on Abram's law to predict the relationship of both the compressive and tensile strength of both concrete and mortars with various water-binder ratio. Accordingly, Abram's model concluded to be applicable in predicting and assessing the relationship between both concrete and mortars with a water-binder ratio. The objective of this study is to investigate the effect of using pigments on mechanical characteristics of concrete. The parameters considered herein are color pigments with different ratios and various water-cement ratios. Three ranges of dosages included 2.5%, 5%, and 7.5%. While three water-cement ratios chosen as follows: 0.4, 0.5, and 0.6. Compressive and flexural strength results at different ages were reported and compared with a control specimen (i.e., 0% pigments). Besides, empirical equations were generated and verified based on Abram's law. The equations present the strength at various w/b ratios, as well as the relationship between compressive and flexural strength.

2. Experimental program

These objectives achieved through the following experimental program. An experimental program set to include the parameters of the investigation. One hundred eighty-nine colored concrete specimens were cast and tested in this experimental program. The samples were cubes of dimensions 10 x 10 x 10 cm and prisms of 10 x 10 x 50 cm. The following section describes the materials, mix design, and, finally, the testing procedure used to fulfill the above-mentioned experimental program. Table 1 shows the total number of the pigmented concrete specimens cast and tested in this experimental program.

Table 1. Experimental program, including the number of tested specimens.

Types of cement	**Additives**			**Compressive strength**		**Tensile strength**
				Numbers of cubes (10x10x10 cm^3)		**Number of beams (10x10x50 cm^3)**
	I.D.	**Pigment Color**	**Pigment Percentage**	**7 days**	**28 days**	
CEM I (Gray)	Control	-	-	3	3	3
	RG2.5	Red	2.5 %	3	3	3
	RG5.0	Red	5.0 %	3	3	3
	RG7.5	Red	7.5 %	3	3	3
	GG2.5	Green	2.5 %	3	3	3
	GG5.0	Green	5.0 %	3	3	3
	GG7.5	Green	7.5 %	3	3	3
W/B RATIO	0.4,0.5,0.6			21 x 3	21 x 3	21 x 3
Total				189		

2.1 Materials

Table 2 represents the characteristics of cement in place of physical and mechanical properties, in addition to the chemical formula for the used pigments admixtures in this experimental program. The resulted values examined and evaluated as per the ECP 203 [18] and ASTM C 183 [19]. Generally, pigments for coloring concrete are naturally organic or synthetic inorganic metal oxides ranging approximately from 0.1 to 1 micron in size that is mixed with cement to add color [9]. In this study, synthetic red and green inorganic powder pigments used for its lower cost and local availability from byproducts of steel and iron manufacturing. However, not all pigments required to have the same color effect, and other pigments might need mixing by other components to tint the color acquired. The pigments are composed of chromium oxide for green pigments and iron oxide for red pigments, as shown in Table 2. All measures required by adopted codes and procedures [18 - 21] to determine the properties of fine and coarse aggregates performed as shown in Table 3 and Figure 1. Figure 1 presents the grain size distribution through sieve analysis tests of coarse and fine aggregates. In contrast, Table 3 presents the physical properties of fine and coarse aggregates, sieve analysis, specific gravity, absorption, and fineness modulus, evaluated according to ECP 203 [18], ESS 1109 [21], ASTM C 70 [22] and ASTM C 128 [23].

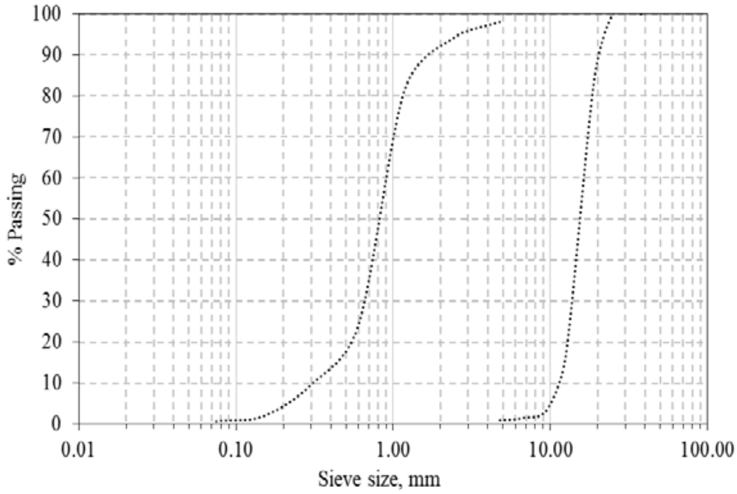


Figure 1. Particle size distribution curve of fine (sand) and coarse aggregates

Table 2. The main characteristics of used cement and chemical formulas of used coloring pigments.

		Cement	Green pigment (Chrome oxide)	red pigment (red oxide of Iron)
Fineness (Blaine) (m^2/Kg)		378	—	—
Specific gravity		3.15	5.1	5.15
Initial setting time		2hr 30 mins	—	—
Final setting time		5hr 57 mins	—	—
Particle size:		—	325 mesh	250 mesh
Shape:		—	Spherical	Spheroidal
Chemical formula		C_3S, C_2S, C_3A and C_4AF	Cr_2O_3	Fe_2O_3
Content(Cr_2O_3)%:		—	≥99.3%	—
Content(Fe_2O_3)%:		—	—	≥99.0%
Purity:		—	99.30%	99.0%
water content		—	0.15%Max	0.20% Max
water soluble matter		—	0.20%Max	0.10% Max
Oil absorption		—	15-25%	21%
Residue on 325 Mesh		—	0.3%Max	0.01%
PH		≈ 13	6 to 8	7
Maximum load (kgf)	3-days	4688	—	—
	7-days	6367	—	—
Compressive strength (MPa)	3-days	17.97	—	—
	7-days	24.66	—	—

2.2 Concrete Mix Design

The concrete mix designed following the British standard BS 5328: Part 2 [24] for specimen preparation instead of the assigned experimental program. The experimental program includes seven concrete mix designs for each water-to-binder ratio (w/b); 0.4, 0.5, and 0.6 by a total of twenty-one mixes. Concrete mixes produced using a mixer capacity of ¾ m^3. Firstly, the control mix (0%) prepared, then three other mixes by percentages 2.5%, 5%, and 7.5% of pigments replaced the cement portion performed for each pigment color; red and green. The mix procedures were as follows: firstly, by mixing the calculated quantities of coarse and fine aggregate. Then, the percentage of pigments added according to the respective design mix.

Table 3. Physical properties of fine and coarse aggregate used.

Property	Fine aggregates	Coarse aggregates
Percent of materials finer than 75 µm (sieve No.200)	2%	-
Bulk Specific Gravity	1.7	-
Apparent Specific Gravity	2.5	2.5
Water Absorption (%)	-	1.2 %
Bulk Density (kg/m^3)	-	1.6
Porosity (%)	-	42.67 %
Los Angeles Abrasion Value (%)	-	33 %

Table 4. Proportions of concrete mixtures in 1 m^3.

Water Binder Ratio	Notes	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Pigments (kg/m^3)		Water (kg/m^3)
					Red	Green	
0.4	Control	331	984	592	0	0	133
	RG2.5	323	959	577	8	0	129
	RG5	315	935	563	17	0	126
	RG7.5	306	910	548	25	0	123
	GG2.5	323	959	577	0	8	129
	GG5	315	935	563	0	17	126
	GG7.5	306	910	548	0	25	123
0.5	Control	455	1164	698	0	0	228
	RG2.5	444	1135	681	11	0	222
	RG5	433	1106	663	23	0	216
	RG7.5	421	1077	646	34	0	211
	GG2.5	444	1135	681	0	11	222
	GG5	433	1106	663	0	23	216
	GG7.5	421	1077	646	0	34	211
0.6	Control	508	1043	628	0	0	305
	RG2.5	496	1017	613	13	0	297
	RG5	483	991	596	26	0	290
	RG7.5	470	965	580	38	0	282
	GG2.5	496	1017	613	0	13	297
	GG5	483	991	596	0	26	290
	GG7.5	470	965	580	0	38	282

Finally, the cement portion added subsequently with water gradually while mixing. After mixing, cubes of dimensions 10 x 10 x 10 cm and prisms of 10 x 10 x 50 cm cast for each mix. Before casting into the molds, the mold's interior surface was scribbled with a thin layer of release agent to facilitate the specimen removal. Compaction took place after smoothening the specimen surface using a trowel. The compaction achieved by using a vibration table to avoid voids penetration into the concrete body. Specimens compacted until any air voids eliminated. It should mention that sometimes the samples might need stroking off to ensure full compaction. Samples left in the mold at a room temperature of 20°C for 24 hours. On the second day, the specimens removed from the molds and placed inside the curing tank for 7 and 28 days. Figure 2 shows the color variation of the cube and prism specimens when 2.5% and 5% pigment content added for both red and green pigments. Figure 3 presents a sample of color developed in cube specimens when changing the w/b ratio (0.4, 0.5, and 0.6) while adding 7.5% red and green pigment. Table 4 provides the concrete mix design for 1 m^3 to the twenty-one mixes and the weight of the pigment used in each blend.

As shown in Table 4, each mix notation denoted by the symbol. For instance, "Control" represents the control mix where no pigments added; 0%. While "RG2.5" donated for the combination with red pigments were "RG" presents, the pigment color and "2.5" represent the percentage of cement replacement with pigments, which is, in this case, 2.5%. Similarly, for mixes with green pigments, the letters "GG" used to represent the color pigment and to assign the cement replacement of 2.5% by pigments, with a value of "2.5" used.

Figure 2. Color variation of cube and prism specimens at 2.5 and 5% pigment content: (a) red pigmented concrete, and; (b) green pigmented concrete.

2.3 Experimental procedure

2.3.1 Compressive strength results

Compressive strength defined the ability of a material to carry the loads on its surface without any cracks or deformation. Concrete under compression tends to reduce its size under the shear effect, while in tension, size elongates due to Poisson's ratio to resist the tensile forces that assess its tensile strength. Usually, concrete has a varying concrete compressive strength between 15 to 40 MPa and higher for commercial and industrial structures. The cube specimens tested using a compression testing machine at 7 and 28 days of concrete age. The load was applied gradually at a pacing rate of 240 kg/cm^2 per minute until the specimens failed after cracks were generated diagonally by shearing, as shown in Figure 4. The compressive strength calculated using the failure load divided by the area of the specimen. Figure 4 clearly shows the diagonal cracks resulted from the conic shape formation due to shearing as a result of compression loading applied to the cube specimen. It should mention that the dimensional factor might influence the cube specimens. The cube specimen, in general, should be dimensioned by 15 x 15 x 15 cm. However, the cube specimen considered in this study dimensioned by 10 x 10 x 10 cm.

2.3.2 Flexural strength

The tensile strength of concrete is deficient when compared to its compressive strength. However, the tensile strength of concrete is one of the primary and essential property which significantly affects the extent of crack size, and propagation path in concrete structures, which affects the serviceability state of beams elements. For instance, in a simply supported beam, the initiation of any crack mainly occurs when tensile stresses developed in the extreme bottom fibers of concrete beams, i.e., when its tensile strength exceeded. Hence, it is crucial to evaluate and assess the tensile strength of concrete. The best feasible way to demonstrate a nearly similar simulation to those of large-scale beams is flexural prisms. The prism specimens tested under four-point loading (two bending points) by using the universal testing machine (UTM) with a pacing rate of 24 kg/cm^2 per minute until complete failure of the specimens, as presented in Figure 5. Figure 5 shows the failure of the prism specimens by splitting into two parts when the failure load reached.

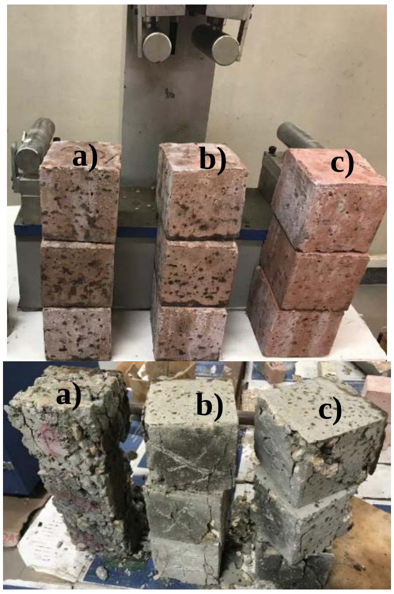


Figure 3. Color variation of cube specimens' for red and green pigmented at 7.5% pigment content with various w/b ratio ratios: (a) 0.4, (b) 0.5, and; (c) 0.6 w/b ratio.

Figure 4. Typical cube specimen failure of colored concrete under the compressive strength test.

Figure 5. Flexural prisms while splitting into two pieces as subjected to four-point loading for (a) green pigmented prism specimens and (b) red-pigmented prism specimens.

3. Experimental results and analysis

Twenty-one concrete mix designed with a variable w/b ratio; 0.4, 0.5 and 0.6. The twenty-one mixes divided into three sets according to the w/b ratio. Each set includes seven mixes; one control, three with a different pigmented replacement ratio; 2.5%, 5%, and 7.5% of each pigmented color; red and green. A total of 189 specimens cast and cured. One hundred twenty-six cube specimens conducted for determining the compressive strength and sixty three prisms for assessing the flexural strength. The following section presents the test results and discusses the generation of the analytical models to predict both the compressive and tensile strength of colored concrete in the future.

3.1 Compressive strength

All cube specimens have exhibited initial cracks at the top and bottom parts. With incremental loading, the cracks at the top and the bottom connected diagonally, forming the shear or a conic shape when reaching the failure load, as it is apparent in Figure 4. Table 5 provides results of cube specimens for compressive strength with various water-binder ratios performed at 7 and 28 days of concrete age.

Furthermore, the table provides the percentage difference of strength between 7 and 28 days age specimens, in addition to the control and those mixes with added pigments (i.e., Relative strength ratio). From Table 5, the 7-days compressive strength results ranged between 13.48 MPa for GG7.5 at 0.4 w/b ratio to 34.28 MPa for GG7.5 at 0.5 w/b ratio, which represents the maximum strength when using pigments. While results revealed in 28 days ranged between 17.94 MPa for GG7.5 at 0.5 w/b ratio and 40.15 MPa for RG7.5 at 0.4 w/b ratio. The optimum strength achieved was the non-pigmented control mix of a w/b ratio of 0.5 with a compressive strength at 28 days of 44.33 MPa.

Table 5. Experimental results of compressive and flexural strength of all specimens

		Compressive strength (MPa)**					Flexural strength (MPa) *	
		7 days			28 days		28 days	
w/b	**I.D.**	**value**	**aging diff**	**Relative strength ratio**	**value**	**Relative strength ratio**	**value**	**Relative strength ratio**
0.4	control	30.44	-	-	43.26	-	8.64	-
	RG2.5	18.33	45.65%	60.22%	40.15	92.81%	6.19	71.64%
	RG5	20.5	59.68%	67.35%	34.35	79.40%	5.98	69.21%
	RG7.5	24.93	81.66%	81.90%	30.53	70.57%	5.27	61.00%
	GG2.5	16.65	53.74%	54.70%	30.98	71.61%	6.53	75.58%
	GG5	13.76	51.81%	45.20%	26.56	61.40%	6.42	74.31%
	GG7.5	13.48	64.65%	44.28%	20.85	48.20%	5.34	61.81%
0.5	control	32.66	-	-	44.33	-	10.52	-
	RG2.5	30.11	80.79%	92.19%	37.27	84.07%	5.51	52.38%
	RG5	29.81	95.58%	91.27%	31.19	70.36%	4.94	46.96%
	RG7.5	24.04	79.55%	73.61%	30.22	68.17%	4.45	42.30%
	GG2.5	31.08	98.11%	95.16%	31.68	71.46%	5.84	55.51%
	GG5	21.57	83.54%	66.04%	25.82	58.24%	4.49	42.68%
	GG7.5	34.28	92.80%	104.96%	17.94	40.47%	5.28	50.19%
0.6	control	19.3	-	-	20.9	-	3.36	-
	RG2.5	16.65	78.95%	86.27%	21.09	100.91%	3.26	97.02%
	RG5	17.5	79.91%	90.67%	21.9	104.78%	3.73	111.01%
	RG7.5	18.25	96.97%	94.56%	18.82	90.05%	3.03	90.18%
	GG2.5	18.01	84.47%	93.32%	21.32	102.01%	2.92	86.90%
	GG5	18.79	83.47%	97.36%	22.51	107.70%	2.86	85.12%
	GG7.5	14.28	76.36%	73.99%	18.7	89.47%	3.38	100.60%

** The specimens are of the cube in shape dimensioned 10 x 10 x 10 cm
*The samples are of prism in shape dimensioned 10 x 10 x 50 cm

For red-pigmented specimens, the w/b ratios of both 0.4 and 0.6 at 7 days age proved that as the partial replacement percentage of cement with red pigments increases, the compressive strength increases, which elaborated by the enhancement of strength to nearly 12% when using the 7.5 % pigments replacement with cement. However, still, the compressive strength achieved when replacing 7.5% of cement with red pigments is less than that of the control specimen by 19% and 5% for w/b ratios of 0.4 and 0.6, respectively, as shown in Table 5 under relative strength ratio. A different trend obtained at w/b ratio equal to 0.5, the compressive strength reduces as the partial replacement increases. Consequently, variable strength results obtained from specimens with a value of 0.5 for the w/b ratio. The compressive strength values at 0.5 w/b ratio are 32.66, 30.11, 29.81 and 24.04 MPa for 0, 2.5, 5 and 7.5% of partially pigmented replacement with cement; respectively.

At 28 days curing, the compressive strength has a significantly different trend while being naturally higher than with specimens of 7 days curing. The compressive strength decreases as the percentage of the red pigment increases. While comparing the control mix, the post trend explained by the acceleration that might have occurred due to the hydration process at an early stage as a result of the chemical composition of the pigments and the high dosage used, leading to strength development. As shown in Table 5, the strength at 7 days curing for the red pigments reached the usual strength limits that are around 70% to 75% of the 28 days strength gain. The percentages on average were relatively 69%, 79%, and 88% of the specimens of 28 days curing for 2.5%, 5%, and 7.5% red pigment replacement, respectively. It is clear at a w/b ratio of 0.6, the aging ratio increases as the partial replacement increases by a percentage of 79%, 80% and 97% for 2.5%, 5% and 7.5% partial pigment replacement. However, this might not occur to all the mixes: for instance, at 2.5% red pigments replacement and a w/b ratio of 0.4, the aging rate was about 46%. The insufficient quantity of water reduces the heat of hydration, which increases the setting time as well as the chemical composition that delayed the strength development at an early age.

Similarly, for green pigments, the strength gain of specimens between 7 and 28-days age was relatively small, indicating the high early development of strength that might have occurred when replacing cement with green pigmented admixtures. On average, the aging ratios between 7 to 28 days were 79%, 73%, and 78%, respectively. It observed that for green pigments at a w/b ratio of 0.4, the behavior is not similar to that of red pigments. The strength decreased by 45%, 55%, and 56% for partial replacements of 2.5%, 5% and 7.5% of the control specimens strength at 7 days age, while the values tend to decrease by 28%, 38% and 52% for partial replacements of 2.5%, 5% and 7.5% of the control specimens strength at 28 days age. Yet, the behavior tends to act differently at w/b ratios of 0.5 and 0.6.

Generally, for all mixes at 28 days age, the behavior was as anticipated; the compressive strength reduces as the partial replacement of pigments increases. At the w/b ratio of 0.6, the different tendency deduced when comparing the control mix with pigmented mixes at 28 days age. The compressive strength values were higher than the control at 5% pigment replacement and then reduced when pigment replacement increased by 7.5%. Moreover, the green pigments do not develop higher strength than the red pigments except at w/b ratio of 0.6.

Despite the low strength, the optimum w/b ratio deduced was equal to 0.6 with a partial replacement of 5% for both green and red pigments to achieve higher and earlier strength as the proper hydration of cement paste and pigments with increasing water content occurs. However, the subsequent increase in water content generally results in lower strength. Consequently, concrete mixes with 0.6 w/b ratio had the lowest strength after 7-days, with only a slight increase in strength after 28-days.

Finally, a relationship between the compressive strength of cube specimens and the w/b ratio generated, as presented in Figure 6.

Figure 6 shows the equation generated from nonlinear regression relating the average compressive strength resulted from cube specimen and the corresponding w/b ratio for each pigmented admixture replacement with cement; 0%, 2.5%, 5%, and 7.5%. Rao (2001) developed a general formula to relate between the 28-days compressive strength and w/b ratio of various cement-sand proportions of 1:2, 1:2.5, and 1:3. Moreover, other authors (Oluokun 1994; Yeh 2006; Metwally 2014) developed a more comprehensive formula for cement-sand proportions of 1:3, 1:4, 1:5, 1:6, 1:7, and 1:8. Similarly, to deduce a relationship between compressive strength σ_c and w/b ratio, all the compressive strength results considered generating a power model as demonstrated by the following Equation (1):-

$$\sigma_c = n_1(w/b)^{n_2} \quad (1)$$

Where σ_c is the average compressive strength of specimens, while n_1 and n_2 are two constants evaluated through a regression on the experimental results obtained. Using the above equation, practitioners can deduce the compressive strength for pigmented concrete according to the percentage of replacement and w/b ratio assigned in their project. Table 6 did not only provide the constants (n_1 and n_2); it also provides the color required on an aesthetic basis.

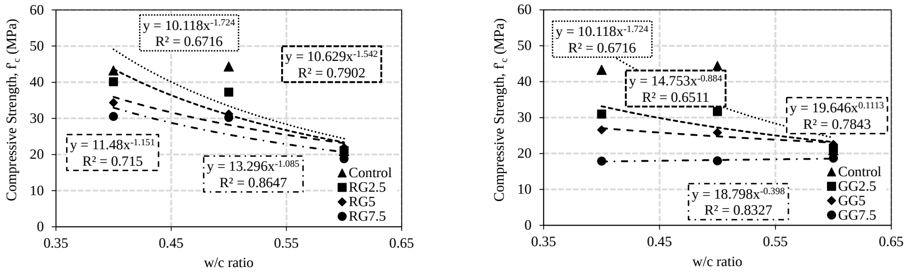
Table 6. Values of strength parameters based on cement/sand and w/b ratio for different pigments percentage replacement of cement.

Cement/ pigments	n_1	n_2	Coefficient of determination	Correlation coefficient	n_3	n_4	Coefficient of determination	Correlation coefficient	Color
0%	10.12	-1.72	0.67	0.82	1.41	-2.21	0.54	0.74	Grey
RG 2.5%	10.63	-1.54	0.79	0.89	1.62	-1.54	0.84	0.92	Clay
RG 5%	11.48	-1.15	0.72	0.85	1.60	-1.34	0.92	0.96	Rust
RG 7.5%	13.30	-1.09	0.86	0.93	2.12	-1.15	0.97	0.99	Amber / Indian Red
GG 2.5%	14.75	-0.88	0.65	0.81	1.23	-1.93	0.81	0.90	Charcoal
GG 5%	19.65	0.11	0.78	0.89	2.12	-1.09	0.73	0.85	Iron
GG 7.5%	18.80	-0.54	0.83	0.91	1.07	-1.98	0.98	0.99	Rhino

The generated equation used for reevaluating the compressive strength, as clarified in Table 6. From Table 7, the predicted-to-experimental ratios calculated seems to provide a good agreement with an average value of 1.02 ± 0.23, 1.01 ± 0.16, 0.91 ± 0.08, 1.11 ± 0.16, 1.01 ± 0.13, 0.73 ± 0.08, and 1.52 ± 0.21 for 0%, 2.5%, 5% and 7.5% for red and green pigmented concrete. The coefficient of variation (CV) is a statistical measure of the dispersion of data points in a data series around the mean. The lower the standard deviation to average return, the better is the generated model used for prediction. The coefficients of variation of these results were 23%, 15%, 8%, 14%, 13%, 11% and 13 % to 0%, 2.5%, 5% and 7.5% for red and green pigmented concrete. Thus, it is much easier for practitioners to choose the suitable w/b ratio based on the required compressive strength.

The coefficient of determination defined by the proportion of the variance in the dependent variable which is predictable from the independent variable, ranges typically from 0 to 1. However, the higher the value near 1, the more accurate the model is. Table 6 provides the coefficient of determination. Most of the benefits range from 0.75 to 1, except for two mixes.

Finally, the correlation coefficient, which measures the strength relationship between two dependent variables. If the values tend to be near +1, this means a strong positive correlation exists. In contrast, if it tends to be near -1, this means a strong negative correlation is governing the relationship between the two dependent variables. However, if it is equal to zero, no association exists. As shown in Table 6, values are around + 0.8 ensures a high significance relationship; however, due to a lower degree of freedom (i.e., One), the significance cannot be accurately counted; therefore, further testing and data to confirm the model is required.



(a) **(b)**

Figure 6. Predicted compressive strength of; (a) Red, and; (b) Green pigmented concrete.

3.2 Flexural strength

Figure 5 shows the failure of the prims after incremental loading until it reaches the failure load for the specimen made with green and red pigments. Table 5 revealed the results of prism specimens for flexural strength with various water-to-binder ratios performed at 28 days. Figure 7 provides a scatter point of flexural strength of prism specimens at 28 days curing versus w/b ratios. From figure 7, the relationship between the flexural strength of pigmented concrete and that of the control mix deduced showing the anticipated trend. As the partial replacement increases, the flexural strength of the pigmented concrete decreases. However, for the 7.5 % green pigments partial replacement specimens at w/b ratio 0.5 and 0.6, the behavior was different. The flexural strength reached that of the control mix. The same behavior deduced for the red-pigmented concrete at 5% partial replacement and a w/b ratio of 0.6. The results ranged from 2.86 to 10.52 MPa. From table 7, the non-pigmented control mix with a 0.5 w/b ratio showed the highest 28-day flexural strength value of 10.53 MPa.

Similarly, the flexural strength equation adopted the same conceptual model used for compressive strength. This conceptual model generates equation relating w/b to the flexural strength of the specimen for 0%, 2.5%, 5%, and 7.5% partial replacement by red and green pigments. The equation based on the power model, which provides a relationship between w/b ratio and flexural strength. Table 8 presents the predicted flexural strength against the experimental values. Equation (2) used to be as follows:

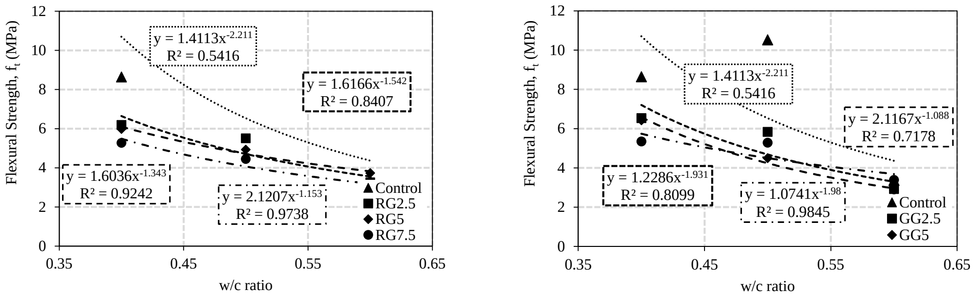
$$\sigma_t = n_3(w/b)^{n_4} \quad (2)$$

where σ_t is the flexural strength, while n_3 and n_4 are two constants. Using experimental results obtained, the values of these constants estimated by regression, as shown in Table 6. The equation adequately predicts the flexural strength of prism specimens by an average value of 1.03 ± 0.38, 1.03 ± 0.12, 0.87 ± 0.06, 1.20 ± 0.1, 1.00 ± 0.17, 1.07 ± 0.21, and 0.96 ± 0.21 on average with coefficient of variation of 37%, 11%, 7%, 8%, 17%, 20% and 22% to 0%, 2.5%, 5% and 7.5% partial replacement by red and green pigments. Similarly, the coefficient of determination provided in Table 6 ranged from 0.75 to 1 expect the control mix was around 0.5. Moreover, the correlation coefficient ranged between 0.75 to 1 showing positive, strong correlation and high significance.

Table 7. Tested and predicted values of compressive strength for pigmented concrete at 28 days.

I.D.	w/b	Experimental results @ 28 days (MPa)	Predicted results @ 28 days* (MPa)	Difference	Predicted / Experimental ratio
Control	0.4	43.26	49.11	-5.85	1.14
	0.5	44.33	33.42	10.91	0.75
	0.6	20.9	24.41	-3.51	1.17
Mean					1.02
SD					0.23
COV					23%
RG2.5	0.4	40.15	43.66	-3.51	1.09
	0.5	37.27	30.95	6.32	0.83
	0.6	21.09	23.37	-2.28	1.11
Mean					1.01
SD					0.16
COV					15%
RG5	0.4	34.35	32.96	1.39	0.96
	0.5	31.19	25.49	5.7	0.82
	0.6	21.9	20.67	1.23	0.94
Mean					0.91
SD					0.08
COV					8%
RG7.5	0.4	30.53	35.93	-5.4	1.18
	0.5	30.22	28.21	2.01	0.93
	0.6	18.82	23.14	-4.32	1.23
Mean					1.11
SD					0.16
COV					14%
GG2.5	0.4	30.98	33.16	-2.18	1.07
	0.5	31.68	27.23	4.45	0.86
	0.6	21.32	23.17	-1.85	1.09
Mean					1.01
SD					0.13
COV					13%
GG5	0.4	26.56	17.74	8.82	0.67
	0.5	25.82	18.19	7.63	0.7
	0.6	22.51	18.56	3.95	0.82
Mean					0.73
SD					0.08
COV					11%
GG7.5	0.4	17.85	30.83	-12.98	1.73
	0.5	17.94	27.33	-9.39	1.52
	0.6	18.7	24.77	-6.07	1.32
Mean					1.52
SD					0.21
COV					13%

*The Predicted values from Equation (1)



(a) (b)

Figure 7. Predicted flexural strength results of; (a) Red, and; (b) Green pigmented concrete.

Table 8. Tested and predicted values of flexural strength for pigmented concrete at 28 days.

I.D.	w/b	Compressive strength (MPa) Experimental results @ 28 days (MPa)	Flexural strength (MPa) Experimental results @ 28 days (MPa)	Flexural strength (MPa) Predicted results @ 28 days* (MPa)	Difference	Predicted / Experimental ratio*	Predicted / Experimental ratio**
Control	0.4	43.26	8.64	10.7	-2.06	1.2	0.9
	0.5	44.33	10.52	6.53	3.99	0.6	0.8
	0.6	20.9	3.36	4.37	-1.01	1.3	1.1
Mean						1.03	0.93
SD						0.38	0.15
COV						37%	16%
RG2.5	0.4	40.15	6.19	6.64	-0.45	1.1	1.2
	0.5	37.27	5.51	4.71	0.8	0.9	1.2
	0.6	21.09	3.26	3.55	-0.29	1.1	1.2
Mean						1.03	1.20
SD						0.12	0.00
COV						11%	0%
RG5	0.4	34.35	5.98	5.49	0.49	0.9	1.1
	0.5	31.19	4.93	4.07	0.86	0.8	1.2
	0.6	21.9	3.73	3.18	0.55	0.9	1.1
Mean						0.87	1.13
SD						0.06	0.06
COV						7%	5%
RG7.5	0.4	30.53	5.27	6.1	-0.83	1.2	1.1
	0.5	30.22	4.45	4.72	-0.27	1.1	1.2
	0.6	18.82	3.03	3.82	-0.79	1.3	1.1
Mean						1.20	1.13
SD						0.10	0.06
COV						8%	5%
GG2.5	0.4	30.98	6.53	7.21	-0.68	1.1	0.9
	0.5	31.68	5.83	4.68	1.15	0.8	1
	0.6	21.32	2.92	3.29	-0.37	1.1	1.3
Mean						1.00	1.07
SD						0.17	0.21
COV						17%	20%
GG5	0.4	26.56	6.42	5.74	0.68	0.9	0.8
	0.5	25.82	4.49	4.5	-0.01	1	1.1
	0.6	22.51	2.86	3.69	-0.83	1.3	1.4
Mean						1.07	1.10
SD						0.21	0.30
COV						20%	27%
GG7.5	0.4	17.85	5.34	6.59	-1.25	1.2	0.6
	0.5	17.94	5.28	4.24	1.04	0.8	0.6
	0.6	18.7	3.38	2.95	0.43	0.87	1
Mean						0.96	0.73
SD						0.21	0.23
COV						22%	31%

*The Predicted values from Equation (2)

**The Predicted values from Equation (3)

3.3 Compressive and flexural strengths relationship

Finally, a linear relationship between the compressive and the flexural strength of the concrete mix observed. Figure 8 shows the linear relationship through curve fitting between the compressive strength resulted from cubes specimen and the corresponding flexural strength resulted from prisms deducing the following equation. Equation (3) generated through the curve fitting was as follows:

$$\sigma_t = n_5(\sigma_c) \tag{3}$$

where σ_c, σ_t is the compressive and flexural strength of each appropriate mix, while n_5 is a constant evaluated by 0.1839. Hence, at the age of 28 days, the flexural strength of red and green pigmented mortar can be estimated using Equation (3), which is a function of the compressive strength. The equation adequately predicts the flexural strength of prism specimens by an average value of 0.93 ± 0.15, 1.20 ± 0.00, 1.13 ± 0.06, 1.13 ± 0.06, 1.07 ± 0.21, 1.10 ± 0.30, and 0.73 ± 0.23 for 0%, 2.5%, 5% and 7.5% partial replacement by red and green pigments. The coefficient of variations were 16%, 0%, 5%, 5%, 20%, 27%, and 31% to 0%, 2.5%, 5% and 7.5% partial replacement by red and green pigments; respectively, showing a good correlation.

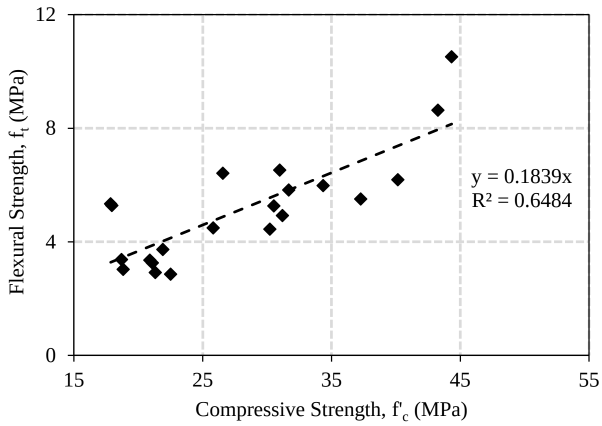


Figure 8. Compressive strength versus Flexural strength results for Red and Green pigmented concrete

4. Summary and conclusions

This paper investigated pigment admixtures and their influence on the mechanical properties of concrete mixes. A twenty-one concrete mix designed with a variable w/b ratio; 0.4, 0.5 and 0.6. The twenty-one blends divided into three sets according to the w/b ratio. Each set includes seven mixes; one control, three with a different pigmented replacement ratio; 2.5%, 5%, and 7.5% of each pigmented color; red and green. The study included 189 concrete specimens from cubes of dimensions 10 x 10 x 10 cm and beams of 10 x 10 x 50 cm. Based on the results and analysis presented herein, the following conclusions were drawn:

1) All cube specimens exhibited diagonal cracks forming the shear or conical shape when reaching the failure load similar to that when using Ordinary Portland Cement (OPC) only.

2) Similar behavior deduced to that when using OPC only during flexural testing. Crack initiated in the middle of the span until failure load.

3) At 7 days curing, as the partial replacement percentage of cement with red pigments increases, the compressive strength increases but lower than that of control. The water-to-binder (w/b) ratio of 0.5 shows the contrary behavior; the compressive strength decreases as the partial replacement of red pigments increases.

4) At 28 days age, the compressive strength decreases as the percentage of red pigment increases.

5) Using green pigments, attained higher values of compressive strength than that of control and reduced when the replacement increased to 7.5% at a w/b ratio of 0.6 after 28 days curing.

6) As the partial replacement of cement with pigments increases, the flexural strength of both red and green pigmented concrete decreases as anticipated.

7) Quantity of water might influence the strength development, accelerating, and retarding the setting time of the hardened and fresh pigmented concrete states.

8) The optimum w/b ratio and percentage of cement replacement with pigments observed were about 0.5 and 2.55% for green pigments to obtain higher and earlier strength development. While, the optimum w/b ratio and percentage of cement replacement with pigments observed ranges between 0.4 to 0.5 and 2.5 to 5% for red pigments to obtain higher and earlier strength development, respectively.

9) The equations used to predict the compressive and flexural strength in the three cases, 2.5%, 5%, and 7.5% pigment - cement replacement were of high accuracy according to the correlation coefficient and the statistical analysis handled.

10) The flexural strength of pigmented concrete is linearly proportional to its compressive strength by factor of 18.5%, which is an acceptable range for empirical estimation to the flexural strength.

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