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Relationship Between Compressive Strength and Non-destructive Tests of Colored Geopolymer Concrete Based on Fly Ash

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P A P E R I N F O

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A B S T R A C T

In this work, some physical and mechanical properties of colored geopolymer concrete based on fly ash were studied. Geopolymer concrete was colored using two types of dyes (chromium oxide which gives green color and iron oxide hydroxide which gives yellow color). The geopolymer concrete samples were subjected to controlled curing conditions at 30°C. At the age of 28 days, all samples were tested under compressive loading and non-destructive tests (NDTs) were also performed such as ultrasonic pulse velocity, Schmidt hammer, dynamic elastic modulus, and dynamic shear modulus. The test results were used to obtain a mathematical relationship between the compressive strength on the one side and the NDTs tests on the other side. This relaionship can be used to estimate the compressive strength of the colored geopolymer concrete by the means of NDTs. In addition, the results proved that the percentage of adding 2% of the dye (for the green color) and 1% of the dye (for the yellow color) is the optimum percentage of the addition.

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1. INTRODUCTION

Geopolymer consists of a natural or a by-product materials that contains alumina and silica in different proportions depending on the type of the raw material, as well as other oxides in small proportions. These materials are chemically activated by mixing with alkaline solutions and can be used as an alternative to ordinary cement [1]. Davidovits [2] found that aluminum (Al) and silicon (Si) in residues such as fly ash, metakaolin, slag, or rice husk ash can react in a process similar to the polymerization process if mixed with alkaline liquids. Thus, Davidovits [2] developed the term geopolymer to explain this reaction.

The geopolymer studies had shown the possibility of reducing CO_2 significantly by up to 80% when compared to the emissions resulting from the use of regular cement [3, 4]. This is one of the modern solutions proposed to address the issue of global warming [5].

Das [6] studied the effect of various factors, namely the ratio of sodium silicate to sodium hydroxide, curing temperature, type of curing, and molarity of sodium hydroxide on the properties of a fly ash-based geopolymer. Lavanya and Jegan [7] studied the durability of geopolymer concrete made from high calcium fly ash and alkaline activators when exposed to a solution of 2% sulfuric acid and 5% magnesium sulfate for up to 45 days. Yahya et al. [8] have studied the feasibility of a fly ash-based geopolymer concrete to which kaolin has been added. Noori et al. [9] studied the relationship between destructive and NDTs for geopolymers based on metakaolin and others based on fly ash and found a relationship between the results of these tests.

Other researchers focused on colored concrete such as Craeye et al. [10] discussed the effect of red pigment on the frostiness resistance of concrete, as well as improvement steps such as adding super absorbent polymers (SAPs) to the fresh mixture. Huang et al. [11] studied the possibility of adding inorganic color paste with proportions of 5%, 10%, and 20% of polyacrylic emulsion to cement mortar. Awadly et al. [12] discussed the effect of adding colored pigments on the different

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properties of concrete, as they used a different group of colored pigments found in the local markets in Egypt.

Accordingly, colored geopolymer concrete could be widely used in some construction applications such as interlocking pavement bricks. For this reason, many researchers had studied the using of fly ash as an alternative to cement, and others have studied the compatibility of using color cement and pigments with geopolymer concrete. The aim of this work is focus on assessing the quality of colored geopolymer concrete by means of nondestructive tests. Also, the current study aims to find a relationship between the compressive strength and the nondestructive NDTs (rebound hammer and ultrasonic pulse velocity UPV) of colored geopolymer concrete fly ash based [13].

2. MATERIALS

2. 1. Fly Ash The Type C fly ash used in this work was imported from UAE origin by Eurobuild company. Tables 1 and 2 show the chemical analysis and physical properties, respectively, of fly ash according to ASTM 618 type C [14].

TABLE 1. Chemical Composition of Fly Ash Type C by XRF (Wt%)

Oxides	Content %
SiO_2	38.63
Al_2O_3	22.16
Fe_2O_3	5.9
CaO	22.3
MgO	6.86
K_2O	0.29
SO_3	0.82
TIO_2	0.58
L.O.I	1.68
Na_2O	0.22
P_2O_5	0.56
	Σ= 100

TABLE 2. Fly ash physical characteristics

Characteristics	Outcomes
Nature of form	Fine powder
Specific weight	2.35
Color	Near light white
Moisture content (%)	1.15
Surface area, cm^2/g	6560

2. 2. Sodium Hydroxide Caustic soda (sodium hydroxide) is a small flake available in the local market. To prepare the solution from these flakes, it is necessary to dissolve (404) g of NaOH flakes in (596) g of distilled water to obtain the required concentration of (14 M) in this work [15].

2. 3. Sodium Silicate Sodium Silicate Liquid is manufactured in the United Arab Emirates. The properties of Na_2SiO_3 are shown in Table 3.

2. 4. Water Tap water was used in this work as additional water to the design mixture for improve workability and obtaining the desired homogeneity.

2. 5. Fine Aggregate Natural sand taken from Karbala region (Al-Ukhaidir region) was used and conformity with ASTM C33 [16].

2. 6. Coarse Aggregate In this work, used crushed natural gravel (with grade 4.75-19.5) for all mixtures as coarse aggregates taken from the Salah al-din region (Al-Nabei area). After conducting the gradient test with sieves for gravel according to ASTM C33 [16].

2. 7. Plasticizer The super-plasticizer, condensed formaldehyde modified with sulfonated naphthalene is necessary for the development of geopolymer concrete and complies with ASTM C494 [17].

2. 8. Pigments Two types of pigment powder were used in this work (FeOH yellow and green Cr_2O_3). In different proportions (0, 1, 2, 3) by weight % of fly ash in the mixture bearing in mind that the pigments are imported from China.

2. 9. Final Preparation of Liquid Alkali After the NaOH flakes are dissolved in water, they are mixed with a Na_2SiO_3 solution where the solutions were stirred for a few minutes and the mixture must be completed at least 24 hours before it is used in the mixtures [18].

TABLE 3. Properties of Sodium Silicate

Description	Value
SiO_2 / Na_2O (%)	2.35 ± 0.05
H_2O (%wt.)	53.4
Na_2O (%wt.)	13.60
SiO_2 (%wt.)	33
Density(g/cm^3) @20° C	2.5
Specific Gravity	1.525
Viscosity (CPS)@ 20°C	800
Appearance	Vaporous

3. LABORATORY WORK

3. 1. Design of Mixtures Seven colored geopolymer concrete mixtures were designed to study the effect of adding different percentages of colored oxides (yellow and green) [18]. Details of fly ash-based geopolymer concrete mixtures are summarized in Table 4.

3. 2. Colored Geopolymer Concrete Mixing Procedure It has been reported that the geopolymer concrete can be manufactured by applying the old traditional methods that were used in the manufacture of ordinary concrete [18, 19]. First, the dry ingredients (fly ash, pigment, fine aggregate, and coarse aggregate) are mixed for 2-3 minutes using an electric mixer (capacity 250 liters), then water, plasticizer, and prepared alkaline liquid are added and all mixed for (4-5 minutes). This mixing procedure of geopolymer concrete was according to a previous study [18].

3. 3. Curing In this work, the samples were placed inside the oven in the laboratory at a temperature of 30 °C [20].

3. 4. Tests

3. 4. 1. Compressive Strength Testing Testing was performed in accordance with ASTM C39 [21] on a specified set of three cylinders, dimensions: (150 mm diameter x 300 mm height) for each colored geopolymer mixture. A hydraulic press (3500 kN) was used as shown in Figure 1. This test was performed after samples were cured when they reached the age of 28 days. The compressive strength can be calculated by applying a simple mathematical relationship:

$$\sigma = \frac{P \quad (in\ N)}{A \ (in\ mm^2)} \tag{1}$$

where:

σ: Compression strength (MPa)
P: Max load applied (N)
A: Area under load (mm^2)

3. 4. 2. Rebound Hammer Test This test requires the surface to be hammered with a Schmidt hammer based on ASTM C 805 [22] as shown in Figure 2 and is performed on a set of cubes of dimensions (150 x 150 x 150) mm^3 each with a geopolymer color mixture ratio. The sample is installed in a pressure tester and subjected to a load of approximately 15% of the expected failure load, and several readings are taken from several locations on the sample surface.

TABLE 4. Design of reference and color geopolymer mixtures

Mix.	FA (kg)	Alkaline Liquids (kg)	Gravel (kg)	Sand (kg)	Added water (kg)	HRSPA (kg)	Pigments (kg)	Na_2SiO_3/ NaOH (%)	Molarity of NaOH
Mr	10	3.544	30.05	14.79	0.95	0.39	0	2.5	14
MY1	9.9	3.544	30.05	14.79	0.95	0.39	0.1	2.5	14
MY2	9.8	3.544	30.05	14.79	0.95	0.39	0.2	2.5	14
MY3	9.7	3.544	30.05	14.79	0.95	0.39	0.3	2.5	14
MG1	9.9	3.544	30.05	14.79	0.95	0.39	0.1	2.5	14
MG2	9.8	3.544	30.05	14.79	0.95	0.39	0.2	2.5	14
MG3	9.7	3.544	30.05	14.79	0.95	0.39	0.3	2.5	14

Figure 1. Test of compressive strength

Figure 2. Schmidt hammer test

3. 4. 3. Ultrasound Pulse Velocity Test (UPV) Test

Ultrasound is one of the most important NDTs. This test was carried out on three cubes of dimensions (150 x 150 x 150) mm using probes at a frequency of (54) kHz, according to ASTM C 597 [23] as shown in Figure 3.

3. 4. 4. Shear Modulus (G_d), Dynamic Modulus (E_d)

Mechanical properties such as the dynamic modulus of elasticity (Ed) and the shear modulus of elasticity (Gd) can be determined by the equations below, which can be applied to measure and estimate the values of the elastic properties of the samples by calculating (VS), which represents the shear velocity as well as (VL) which means the velocity of Longitudinal wave [24].

$$\mathrm{Ed} = \frac{\rho Vs^2(3Vl^2-4Vs^2)}{Vl^2-Vs^2} \quad (2)$$

$$\mathrm{Gd} = \mathrm{Vs}^2 * \rho \quad (3)$$

when:

E_d: Dynamic modulus (GPa).

G_d: Shear modulus (GPa).

Vl: Longitudinal velocity (m/s).

Vs: Shear velocity (m/s).

ρ: Density of the samples (kg/m^3).

It is possible to calculate the value of the speed of the transverse waves using (S-wave transducer probes), as shown in Figure 4.

Figure 3. U P V direct test

Figure 4. UPV test by using (S-wave) transducer

4. RESULTS AND DISCUSSION

4. 1. Compressive Strength

The results of the compressive strength samples from a group of geopolymer concrete mixtures of two colors in various proportions are summarized in Table 5.

Pigments in the percentages of (0, 1, 2, 3)% were added for yellow and green colored samples. Addition of color (2%) gave the highest value in the compressive strength of green-colored geopolymer concrete, but when adding more than (2%) of green color, the compressive strength results decreased. However, the use of 1% of yellow color within geopolymer concrete was the best ratio because it achieved the highest compressive strength, but when increasing the color percentages, the opposite behavior will appear in the compressive strength results as the result showed a gradual decrease in compressive strength. These effects are due to the following reasons

- The pigments used (yellow and green) tend to absorb water molecules before they interact with FA because their molecules are finer than FA molecules. Therefore, the process of reducing water that interacts with the basic binder FA tends to improve the compressive strength and on the contrary, increasing the amount of water leads to reducing the bonding between the molecules of the basic bonding material [25].
- Adding pigments as a filler will reduce the pores inside the total volume of the colored geopolymer to some extent and lead to an increase in the compressive strength of geopolymer concrete. However, when adding an excessive amount of it increases above the point and the saturation limit (excessive addition of pigment will reduce the pressure due to the agglomeration of these particles pigment. Which leads to the formation of a region of separation and weakness) inside the colored geopolymer concrete because the pigments are non-pozzolanic materials. Thus, the pigments are not enter into the chemical reactions that occurs (polymerization) inside the colored geopolymer concrete [25].

TABLE 5. Compressive strength readings for samples of geopolymer concrete mixtures

Mixes	Compressive Strength(N/mm^2)
Mr0	37.36
MY1	38.47
MY2	36.80
MY3	34.86
MG1	38.07
MG2	40.42
MG3	37.28

4. 2. Rebound Hammer In Table 6, the results of the rebound hammer test were listed.

In general, addition of pigments leads to higher values of geopolymer concrete rebound number when added with a small percent, and this increase in values is due to the role of pigments that act as fillers for the internal and surface pores of the samples and thus reduce the surface roughness of the samples. The highest values of rebound number were obtained when using green pigment (2%) by weight of fly ash and (1%) by weight when using yellow pigment.

But when increased the percentage of additional pigments, can lead to the agglomeration of the pigments and cause areas of isolation and areas of less interconnection due to the decrease in the binder, and this, in turn, reduces the value of the rebound number.

4. 3. UPV Test The results of the UPV test are shown in Table 7.

From the above table, it cab be notice that there is an increase in the speed of pulse penetration when adding pigments, but with an increase in the percentage of additional pigments, the values of the wave penetration speed begin to decrease, and the reason for this is attributed to two factors:

TABLE 6. Results of Rebound Number for colored geopolymer concrete mix

Mix.	Results of Rebound Number
Mr0	39.12
MY1	44.88
MY2	43.01
MY3	40.45
MG1	42.21
MG2	43.90
MG3	40.07

TABLE 7. The results of the UPV test were listed

Mixes	UPV(m/s)
Mr0	3630
MY1	3691
MY2	3631
MY3	3528
MG1	3708
MG2	3736
MG3	3672

- Positive effect: It is due to the role of pigments in filling the voids and pores due to having a higher surface area than fly ash.
- Negative effect: When the percentage of pigments increases, this can lead to the agglomeration of pigment molecules, which replaces the binder (where the binder plays a role in the bonding and convergence of the molecules of the other components of the mixture and increases its density).

4. 4. Dynamic Modulus, Shear Modulus The results of the NDT calculations are shown in Table 8.

It is clear from Table 8 that the dynamic modulus of elasticity and the dynamic shear modulus behave in similar behavior to the UPV because the dynamic modulus of elasticity and the dynamic shear modulus are directly proportional to the UPV (based on the mathematical equations).

4. 5. Mathematical Relationship Between Compressive Strength Test And NDT (RN and UPV) An equation was derived from the experimental data in this study using Curve Expert Pro 2.7.3 program for colored geopolymer concrete (based on fly ash) is:

$$\textit{Compressive strength} = a + RN^b \times UPV^C \tag{4}$$

TABLE 8. Density, longitudinal velocity, shear velocity, dynamic young modulus, and shear modulus results of colored geopolymer concrete mix

Mix.	Density (kg/m^3)	Longitudinal pulse velocity(m/s)	Shear pulse velocity (m/s)	Dynamic elastic modulus (GPa)	Dynamic modulus of shear (GPa)
Mr0	2410	3630	2268	29.25	12.39
MY1	2437	3691	2278	30.15	12.64
MY2	2411	3631	2253	29.05	12.23
MY3	2372	3528	2240	27.66	11.90
MG1	2451	3708	2284	30.54	12.78
MG2	2464	3736	2290	30.98	12.92
MG3	2430	3672	2267	29.77	12.48

where:

a= -97.13
b=0.026
c=0.586
Correlation Coefficient: 0.96

Equation (4) is limitted only for geopolymer concrete with compressive strength ranging between 30-40 MPa. This is due to the fact that the geoploymer concrete may consist of various ingredients with different characteristics that could change its mechanical and physical properties (see Figure 5).

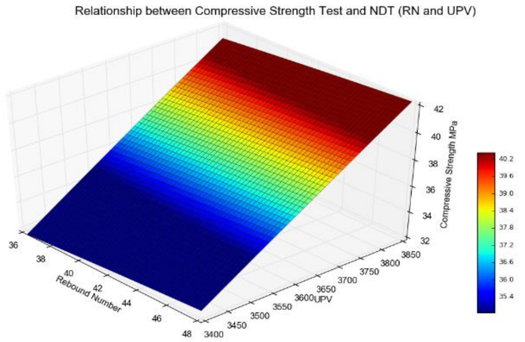

Figure 5. Mathematical relationships between (RN and UPV) test and the compressive strength test of colored geopolymer concrete

5. CONCLUSION

According to the experimental results shown above, the optimum percentage of adding chromium oxide is 2% of the weight of the fly ash, and the optimum percentage of adding iron oxide hydroxide is 1% of the weight of the fly ash, because the pigments addition of more than the above-mentioned percentages causes a deterioration of the colored geopolymer concrete properties. While in the case of adherence to the percentages as mentioned above, an increase in compressive strength characteristic was obtained by 8% and 3% for both green and yellow colors, respectively. Also, a mathematical relationship was found between the NDTs and the compressive strength, through which we can estimate the compressive strength through the NDTs.

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Persian Abstract

چکیده

در این کار برخی از خواص فیزیکی و مکانیکی بتن ژئوپلیمری رنگی بر پایه خاکستر بادی مورد بررسی قرار گرفت. بتن ژئوپلیمری با استفاده از دو نوع رنگ (اکسید کروم که رنگ سبز می دهد و اکسید آهن هیدروکسید که رنگ زرد می دهد) رنگ آمیزی گردید. نمونه های بتن ژئوپلیمری تحت شرایط بعمل آوری کنترل شده در دمای ۳۰ درجه سانتیگراد قرار گرفتند. در سن ۲۸ روزگی، تمامی نمونه‌ها تحت بارگذاری فشاری مورد آزمایش قرار گرفتند و آزمایش‌های غیرمخرب (NDTs) مانند سرعت پالس اولتراسونیک، چکش اشمیت، مدول الاستیک دینامیکی و مدول برشی دینامیکی نیز انجام شد. از نتایج آزمایش برای به دست آوردن یک رابطه ریاضی بین مقاومت فشاری از یک طرف و آزمون‌های NDTs از طرف دیگر استفاده شد. این رابطه را می توان برای تخمین مقاومت فشاری بتن ژئوپلیمر رنگی با استفاده از NDT ها استفاده کرد. علاوه بر این، نتایج نشان داد که درصد افزودن ۲ درصد رنگ (برای رنگ سبز) و ۱ درصد رنگ (برای رنگ زرد) درصد بهینه افزودن است.