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Properties of pigmented concrete

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Properties of Pigmented Concrete

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"For Ehlimana, Haya and Ammar"

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ABSTRACT

Concrete is a major construction material known for its strength and durability. For long it has been considered an aesthetically unfriendly and dull material that should be hidden beneath layers of plaster and paint. Pigmented concrete is a relatively new type of concrete that offers higher chromatic qualities for architectural projects than paints. With the recent trend of urban color aiming at rendering cities with attractive color schemes using rich texture offered by conventional construction materials, pigmented concrete has become a preferable choice for building exteriors. Today, renowned architects use pigmented concrete that fulfils aesthetic and technical requirements in addition to its advantages in terms of maintenance and durability.

This study aims at achieving a better understanding of pigmented concrete and exploring its potential properties and applications. The main objective is to assess the impact of parameters such as cement color and pigment dosage on mechanical properties and color stability. Concrete specimens were made using grey and white cements and three different dosages of red, yellow and green pigments. The testing scheme includes fresh, hardened concrete and durability properties as well as color performance assessment. These tests were developed specifically for the purpose of this research work.

On the whole, pigmented concrete had lower mechanical properties than conventional concrete mixtures, yet, the reduction in strength still allows many of these mixtures to be used in structural concrete. The intermediate dosages of used pigments seem to be more adequate for both mechanical properties and color stability. Pigmented mixtures with white cement had somewhat less mechanical properties possibly due to the cement manufacturing scheme while pigmentation effect was more vivid than mixtures with grey cement. Compared with control unpigmented mixture, the average drop in compressive strength ranged between 10 percent for pigmented grey concrete mixtures and 20 percent for pigmented white concrete mixtures. The technique used for color assessment and color stability with time has repeatable results and is recommended for future use in similar studies. Applicators are encouraged to use pigmented concrete for applications involving long term pigmented effect with minimal concrete finishes.

Keywords: (Concrete, Architectural, Pigments, Color Measurement, Digital Imaging)

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CHAPTER 1

INTRODUCTION

1.1 Background

The word concrete is derived from the Latin *concretus* that means "having grown together". Concrete is one of the oldest building materials which is widely used in construction around the world. It was first used by the Romans to build the Dome of the Pantheon which asserts not only concrete's durability and strength but its architectural possibilities as well. Mixing of mortar with small stones to produce a hard monumental mass was described by various architects from the Roman architect Vitruvius to Renaissance architects like Alberti and Palladio. Joseph Aspdin patented "Portland Cement" in 1824 even though it was not used as a bonding agent but as stucco that simulates Portland stone. Modern Portland cement was not produced until 1844 and its use for engineering purposes started few years afterwards (Collins, 2004). Special types of concrete include self compacting concrete SCC, high performance concrete HPC, ultra-high performance concrete UHPC, light weight concrete and shrinkage compensating concrete. Self compacting concrete is characterized by its high workability, thus eliminating concrete compaction process. It flows under its own weight into the formwork without segregation. Pigments can be added to SCC for architectural applications. A recent example is Rome's Museum of Modern Arts designed by Zaha Hadid (Corinaldesi et al. 2012). High performance concrete was developed to tackle structural design and durability issues. Using a mix design rich with cementicious materials and very low w/c ratio, compressive strength can reach up to 97 MPa. Improved properties include freezing and thawing durability, scaling resistance, abrasion resistance and chloride ion penetration (Russel and Ozyildirim, 2006). While ultra high performance concrete was first introduced in the mid 1990s with its superior environmental resistance and compressive strength that exceeds 150 MPa. Using fiber reinforcement may also improve its tensile strength to reach 15 MPa (Wille et al. 2011).

1.2 Architectural Concrete

The American Concrete Institute defines architectural concrete as "*concrete exposed as an interior or exterior surface in the completed structure, which definitely contributes to its visual character, and is specifically designated as such in the contract drawings and specifications.*" Concrete's aesthetic can be controlled during or after casting. The use of pigments, colored cements and aggregates offer a variety of colors. While different textures and finishes can be obtained with exposed aggregates design that can be sand blasted or acid etched before final curing. After concrete setting its flat surfaces can be sandblasted or brush-hammered. Architectural concrete finishes also play a crucial role as an alternative for cladding, plastering and painting. Concrete and cement manufacturing process is accountable for about five percent of the global carbon dioxide emissions. Thus, using architectural concrete for building construction and finishing may have a role in decreasing generated pollution. Eliminating the use of finishing plaster would result in less energy to manufacture cement, less water used for mixing and general waste reduction. Another aspect is eliminating volatile organic compounds emissions (VOCs) present in construction paints (Binggeli, 2011). Architectural concrete can be divided into three classes; untreated, treated and decorative concrete art.

1.2.1 Untreated Concrete

The principle visible constituent of untreated surfaces is mortar color depending on cement used and presence of pigment.

Pigmented Concrete

In 1871 the Royal Institute of British Architects was urged by Sir Arthur Blomfield regarding the challenge of building concrete walls with such craftsmanship that the decorative covering would be unnecessary. Blomfield explained that by using fine concrete at the surface that is left untouched after formwork is removed would abolish the use of plaster. He argued that even though forms left marks on concrete surface, these marks should be clearly defined and used to vary the composition and color of concrete. He suggested the use of fine quartz or granite, colored sands and fine sea-shingle to achieve this aim (Collins, 2004). Today, concrete is produced in color using pigments. Pigments are solid particles with size less than 1µm in diameter that enables them to refract light and provide color. Pigments have to be dispersed evenly in the concrete matrix to become effective. Pigments are widely classified into organic or inorganic. While organic pigments are stronger and brighter inorganic pigments are light stable, chemically stable and much cheaper (Ravikumar et Al. 2012). The largest inorganic pigment used nowadays is synthetic iron oxide, accounting for almost 73% of the market by volume. Lanxess (formerly Bayer) produces half of the world's production (HIS, 2011). Using iron scrap as raw material and fibrous leftovers of sugarcane as fuel, the production process is considered environment friendly and carbon neutral thus contributing to sustainability (Lanxess.com, 2013). Construction industry uses pigments in various concrete elements, cast-in place as well as precast in addition to pavers and concrete roofing tiles. Integrally pigmented concrete is established as an elegant and versatile material. It can be produced successfully with both white as well as grey cement without color fluctuations. Better appearance of pigmented grey concrete can be produced using white titanium dioxide pigment mixed with black iron oxide (Weber et al. 2009). Renowned architects are using pigmented concrete in design and construction of major projects. Sir Norman Forester used red pigmented concrete for the construction of Arsta Bridge at the Stockholm's main train station in Sweden. It fulfilled technical requirements for strength, long spans, flowability in addition to its advantages in terms of maintenance and durability. Another aspect for the use of red pigment was to celebrate the traditional Swedish wooden house color, Falun red, used since the 16th century. The formwork was manufactured using solid wood planks and boards that were covered with cement and red pigment slurry to avoid color variation at the finish surface as shown in Figure 1.1.

Figure 1.1 Arsta Bridge designed by Sir Norman Forester (Lanxess.com, 2013)

The German architect Fritz Auer used pigmented red concrete to design ESO Hotel in Chile's Atacama Desert achieving another goal of aesthetically integrating the building with the tones of surrounding landscape as shown in Figure 1.2. With the extreme variation between day and night, thermally inert properties of such concrete structures provide a controlled interior temperature (Lanxess.com, 2013). Concrete stores thermal energy over the day and gradually transforms it to the hotel room at night (Binggeli, 2011).

Figure 1.2 ESO Hotel blending with desert tones (Lanxess.com, 2013)

Soccer City Stadium at Johannesburg, South Africa is one of the largest arenas worldwide that can accommodate about 89,000 spectators and is considered state of the art stadium architecture. Originally constructed in 1984, it was renovated to host 2010 World Cup. A new façade was constructed using fiber reinforced concrete panels with different red pigment shades. The major concern behind this choice was the local climate where strong winds and dust create a continuous sandblasting effect that conventional coatings cannot withstand. Figure 1.3 shows the stadium's façade with different shades of pigmented red panels also symbolizing the South African cultural diversity (Lanxess.com, 2013).

Figure 1.3 South Africa's 2010 World Cup City Stadium (Lanxess.com, 2013)

White Concrete

Grey concrete always caused confusion as few professionals considered it presentable due to its dull color of grey cement in addition to the texture produced by the formwork (Binggeli, 2011). Materials, workmanship, air pollution and climate are major factors affecting grey concrete aesthetic (Al-Anany, 2005). White cement is a cement type that conforms to ASTM C150 with an added limitation of containing no more than 0.5% of iron-oxide by weight. Generally, compressive strengths of white and grey cement are similar and thus white cement is used to produce white concrete. Fine aggregates act as a coloring pigment thus exert an important influence on the final concrete color. Thus it is crucial to specify manufactured fine aggregate like crushed white limestone or quartzite with limited iron- oxide content. Coarse aggregate has less influence on color but should be specified for surface exposed to surface abrasion or vehicular traffic. Mixing water also must be free of iron. Admixtures and form release agents might cause discoloration thus it is recommended to specify appropriate products for use in white concrete (M.K.Hurd, 2001). White concrete can be used diversely indoors and outdoors as an architectural alternative to grey concrete as it bounces light from both artificial and natural sources thus reducing the amount of energy use (Environmental Design & Construction, 2004). White concrete provided a solution for facades subjected to extreme alpine weather at a natural park visitor center in Switzerland. The building radiates with constant presence with its facades perceiving different shades of color with changing weather and position of the sun (Concrete International, 2010). It was also used for white parapets for Pennsylvania highways. With its better visibility during dark and/or rainy nights accidents were reduced. This resulted in replacing the conventional use of white coating on grey concrete parapets eliminating periodic maintenance for coating (M.K.Hurd, 2001).

1.2.2 Treated Concrete

This is achieved by a variety of techniques for removing of surface mortar and exposing the aggregates either wholly or partially generating different textures. Additional effects are achieved when applied to pigmented concrete (Al-Anany, 2005).

Exposed Aggregate Finishes: Categorized as light, medium or heavy, this technique of concrete surface removal reveals the underlying aggregates.

Architectural Profiling Finishes: Produced using panels or profiles shaped within concrete formwork with geometric or abstract patterns resulting in panels with different surface planes.

Hammered-Rib Finishes: Produced by casting concrete in a ribbed formwork then fracturing the projecting ribs by a hammer. Resulting would be roughened ribs that hide concrete imperfections or weathering stains.

1.2.3 Decorative Concrete Art

Architecture and sculpture always had an affinity; with the rise of Art Nouveau by the end of Nineteenth century, architectural forms were hand carved first in structural masonry walls. The possibility of molding concrete due to its plasticity had been its most obvious property. Despite molding limitations, important exploitations of concrete took place; Antonio Gaudi managed to cast his less complicated forms in concrete at Casa Mila as shown in Figure 1.4. While the most successful attempts were achieved in Paris, Auscher's store and apartment block and Felix Potin's building shown in Figure 1.5 (Collins, 2004). Today, Concrete decorative art is recognized worldwide.

Figure 1.4 Rooftop of Gaudi's Casa Mila(Collins, 2004)

Figure 1.5 Felix Potin's concrete decorations (Collins, 2004)

Vertical decorative plates can be done on blank walls, using bonding agent walls are first covered with scratch mortar coat then a carving mixture is applied. Artists begin detailing by carving concrete before the final setting of concrete. Finally a reactive stain is applied to provide final effects as shown in Figure 1.6 (Tosalt, 2011).

Sculptures of pH-neutral concrete using marine-grade cement and fiber reinforced are installed underwater to form reef structures for marine life to colonize, thus helping environmental conservation of existing reefs as shown in Figure 1.7 (Concrete International, 2011).

Figure 1.6 Finished vertical decorative installation by carving concrete (Tosalt, 2011)

Figure 1.7 Life-sized pH-neutral concrete sculptures that help coral growth (Concrete International, 2011)

1.3 Statement of the Problem

Relatively little work has been conducted in the domain of pigmented concrete. Despite recent tendency of rendering more attractive cities with color schemes, addressing pigmented concrete color performance and stability has been seldom tackled. The influence of inorganic pigment dosage on hardened concrete properties and color durability has not been sufficiently studied. Meanwhile, There has been no well documented technique to assess color stability and color hue resulting of addition of color pigments.

The aim of this study is to compare the performance of pigmented concrete using grey, white cement, different color pigments at varying dosages with conventional concrete and to propose a solid method of color assessment of pigmented concrete. This work should thus provide a better understanding of the building exterior when pigmented concrete is used considering the same aspects of evaluation when compared with conventional concrete.

1.4 Work Objectives and Scope

The main objectives of this work are as follows:

- To assess the pigmented concrete properties associated with using two different types of ordinary Type I Portland cement; grey and white Portland cement.
- To hold a comparison between various dosages of inorganic pigments; red iron-oxide, yellow iron-oxide and green chromium-oxide as well as studying their impact on the resulting fresh and hardened concrete properties.
- To evaluate the impact of pigmented concrete exposure to chlorides in comparison to conventional concrete.
- To establish some means to estimate pigmented concrete color performance and stability when used in building exteriors.

To meet these objectives, an experimental program was designed involving nineteen concrete mixtures, which were prepared using two different type I ordinary Portland cements (grey and white) together with conventional concrete. Three different types of inorganic pigments were added to grey and white cement concrete mixtures. In each mixture, three pigment dosages were added to investigate their influence on concrete properties and pigmentation. The testing scheme associated with this work involved fresh and hardened concrete testing. For fresh concrete testing slump, air content and unit weight tests were performed. As for hardened concrete testing, compressive strength, flexural strength, rapid chloride permeability test. To monitor color performance a visual assessment was performed in addition to a digital imaging process for acquisition and assessment was conducted.

CHAPTER 2

LITERATURE REVIEW

In this chapter, relevant literature and studies are briefly reviewed and presented.

2.1 Color and Architecture

Architecture today no longer responds neutrally or sympathetically to natural landscape but creates its own with its breadth and scale. In his project colored with pigments, La Cite Radieuse, the French pioneer of architecture Le Corbusier declared that the presence of color is a true sign of life that renders everything with a new sparkle. Revival of architectural color began in Europe and particularly in France where new towns such as Cergy Pontoise, Le Verdreuil and Evry came to be planned and executed in painted color. Other architectural elements were used to economically renew hearts of old cities like street furniture, lighting and urban color at the cities of Lyon and Nimes. Since the 1970s architectural color has become an added factor in the construction environment experience. Till the nineties, Paints had offered an inexpensive and easy means of rendering buildings in color, especially used for poor architecture to enrich its experience. But paints were less used in higher quality architectural projects. Such projects depended mainly on a subtle inherent chromatic sophistication of conventional materials on the building exterior or envelope. The scheme was to experiment with new materials to shock, provoke and catch attention as well as challenging manufacturers to produce more technologically advanced construction materials and finishes. As a result, a completely new expression of architecture evolved incorporating not only building function but playing an important role in a marketing strategy. Image has become a function or "autograph" of architecture and its designer. Architecture became an object of art that shows in works of architects like Renzo Piano, Jean Nouvel and Frank Gehry. For example, Gehry's flowing use of titanium at the Guggenheim Museum in Bilboa has become a prototype for a landmark building that transformed a poor Spanish port into a popular tourist destination. Color is now seen as an architectural attribute along with form, space, volume, shape and light. Color that does not only reflect mere pigmentation but those chromatic nuances caused by texture, reflectivity, gloss and patina of natural materials added to the state of the art finishes as shown in Figure 2.1. Architectural color is not limited to daylight experience anymore. Another color phenomenon is seen in today's cities uses programmed choreography of dynamic after-dark colored light. With color the creation of space, scale, direction and orientation is possible. Color may reinforce or weaken different shapes of structures. Color opens up the senses, feelings and perceptions (Porter and Mikellides, 2009).

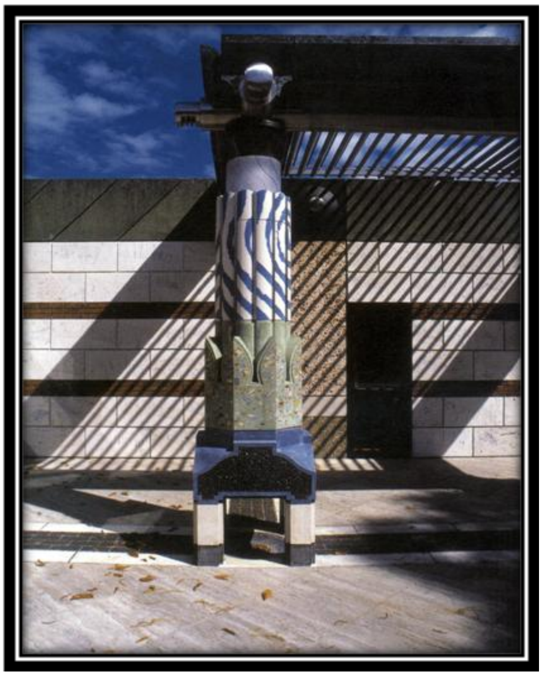

Figure 2.1 A column on Millennium Verandah designed by John Outram (Porter and Mikellides, 2009)

Figure 2.2 Computer-controlled color changing lighting concept at Burj Al Arab tower in Dubai (Porter and Mikellides, 2009)

2.2 Color at the City Scale

2.2.1 Turin Color Plan

European cities developed a process employing local materials that limited architectural expression until early nineteenth century. The color decision was controlled by an inexpensive process of applying local deposits of colored earth pigments creating a color map indentifying certain colors with particular regions. Brighter colors like blues and reds were associated with wealth as their price ranged between ten to hundred times the price of common earth pigments. Color plans for cities first appeared at the city of Turin, Italy. Historical color plans carried out between 1800 and 1850 were found in the city archives. The concept involved specifications for coordinated color setting with a basic palette of 80 hues forming a continuous but changing colorful experience as shown in Figure 2.3. The palette imitates rich building materials like marble, granite and terracotta. Today 10,000 facades have been restored according to the original plans directed by the architect Giovanni Brino. Brino points out the difference between the quality of acrylic paints found in many restoration projects and traditional mineral pigments. Lime-wash and lime stuccoes are entirely compatible with the nature of walls producing mortar with softer tints than acrylic paints. Traditional pigmented stuccoes also bond perfectly to the walls and attain moisture permeability travelling from inside to outside. Acrylic paints create a moisture barrier and over several years become fractured and eventually detach (Porter and Mikellides, 2009).

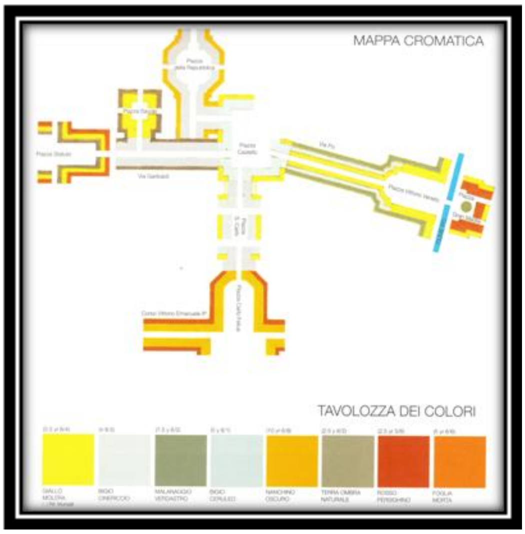

Figure 2.3 Turin Color Plan showing processional routes with designated colors (Porter and Mikellides, 2009)

2.2.2 Kirchsteigfeld Color Plan

Kirchsteigfeld was a new district of Potsdam built between 1994 and 1997 to house 7500 residents as a part of Germany's reunification program. The original design slogan of Master planners Rob Krier and Christoph Kohl was "unity in diversity". Twenty five architectural firms were to individually design and color the new city to induce harmony and unity. Guidelines were set for a color concept aiming at creation of chromatic homogeneity. The concept was to provide color discrimination between streets and squares and public, private and semi private spaces using a color palette of six color families with ranges of red, yellow, blue, grey and white variations comprising 65 hues. Green was not included in the palette but provided lively by the widespread landscape. The strategy involved the extensive use of existing local architectural color, for example yellow ochre found in traditional Potsdam and oxide reds in Old Potsdam in order to clarify the urban space structure in a timely spirit. The basic concept of Kirschsteigfeld color plan assigned the spacious central area and its market square and recreational zones with oxide red range. From this red core, hues gradually lighten from yellow ochre to more pale whitish color on the peripheral ring road. Yellowish color on cloudy days tends to show bright sunny appearance while the town's red center induces a sense of activity and arousal. Finally a blue range was reserved for use for buildings located at plan corners were facades open up to reveal courtyards. The Kirschsteigfeld color strategy succeeded at creating a contrasting diverse architecture while achieving visual chromatic continuity as shown in Figure 2.4 (Porter and Mikellides, 2009).

Figure 2.4 Kirchsteigfeld colored center zone (Porter and Mikellides, 2009)

2.2.3 Environmental Color

Challenged by the anonymity of concrete, Jean-Philippe Lenclos devised a comprehensive analysis to set a code for environmental color. Investigation begins with the classification of natural and architectural color across the diverse regions, climates and buildings. Phase one is aimed at collecting color samples from sites within the region in question. Fragments of different materials from roofs, walls and paints in addition to rocks, vegetation and earth are gathered. Phase two is a long assessment for all collected samples were they are translated into painted color samples that are further classified and regrouped into "color maps". Phase three presents the applied color theme and vocabulary appropriate for each region. This methodology was further applied by Lenclos in Japan then it spread worldwide (Porter and Mikellides, 2009).

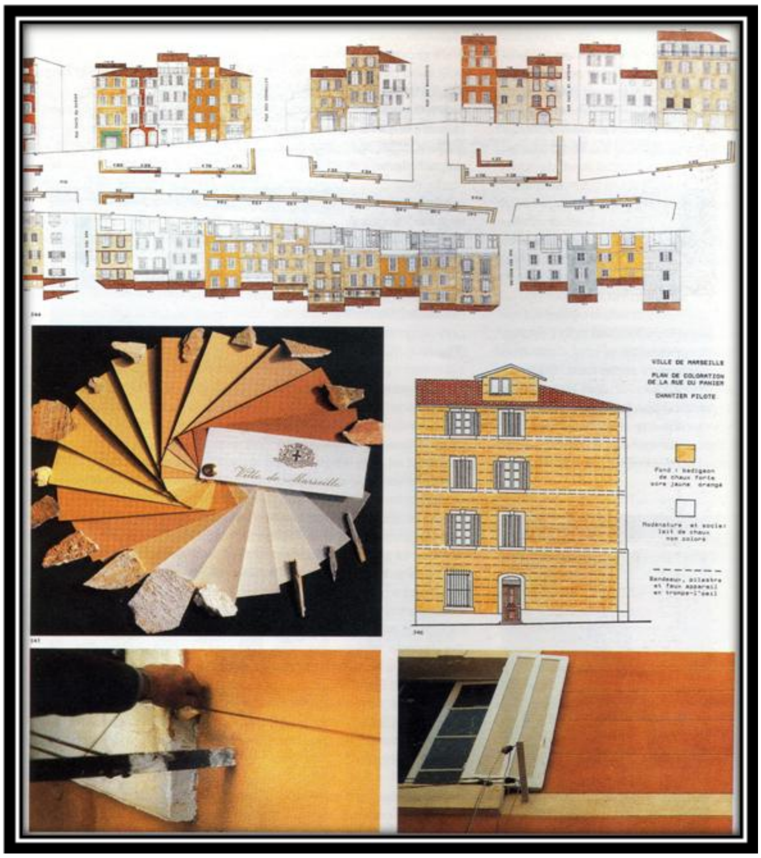

Figure 2.5 Urban mapping of Marseilles city (Porter and Mikellides, 2009)

2.3 Decorative Concrete Applications and Finishes

2.3.1 Integral Colors

A coloring agent is added during mixing to produce integrally colored concrete. This results in a visible color remaining throughout the concrete member where there are saw-cuts, chips or traffic worn out areas. Most integral colors are prepackaged either as dry powdered pigments or as liquid coloring admixture that must be thoroughly dispersed throughout the concrete mix (Ball and Decandia, 2002).

Figure 2.6 Residential pool area uses integrally colored concrete that creates a natural look with surrounding environment (Forgey, 2005)

2.3.2 Dry-shake Color Hardeners

Dry-shake color hardeners provide a concentrated vibrant color at the surface with a maximum depth of 3mm improving concrete's resistance to weathering and abrasion. Color hardeners are applied on the surface of freshly placed concrete and are widely used for stamped concrete to achieve desired surface textures. They are used as a base color with an antiquing release agent. Releasing agents are applied to stamping tools and concrete surface to facilitate the process. A darker release color would blend with lighter colored dry-shake hardener creating depths and shadings in the pattern as a portion of the releasing agent becomes embedded in the surface of concrete and is eventually trapped by the hardening concrete. Antique looking appearance is obtained when concrete surface is later washed and sealed (Ball and Decandia, 2002).

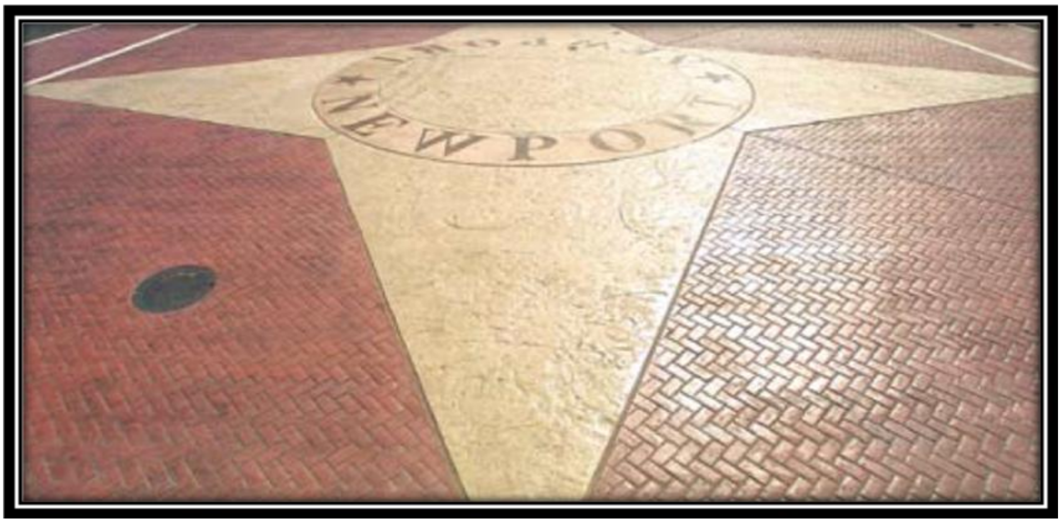

Figure 2.7 Brick pattern produced using a terra cotta color hardener and grey release while the star area was imprinted with a slate skin colored with buff hardener and grey release. Brass letters were embedded in plastic concrete (Boyer, 2007)

2.3.3 Reactive Penetrating Stains

Penetrating stains are reactive penetrating chemicals that create uneven, variegated or translucent color in an artful manner much like that of natural stone as shown in Figure 2.8. Stains can be applied to existing or new, colored or uncolored concrete surfaces. The variegated colors stains have unique results depending on concrete texture, age, chemical composition, porosity and initial concrete color but without affecting concrete performance (Boyer, 2002).

- Acid-based stains are a mixture of water, hydrochloric acid and acid-soluble metallic salts that would react with calcium hydroxide in concrete to produce earth-tone colors (Boyer, 2007). They are applied between 14 to 21 days or more after concrete placement depending on desired stain result. Concrete curing and surface protection are essential to the success of the chemical staining process. Their color may change with time especially when exposed to moisture hence they require a quality sealer and periodic maintenance (Rodgers, 2004).

Figure 2.8 Variegated appearance of chemical stains using classic accents (Palmer Jr., 2007)

- Water-based stains penetrate the surface of concrete depositing colored pigments in its pores resulting a variety of brighter and more uniform colors than those produced with acid-based stains (Boyer, 2007).
- Water and solvent-based dyes contain very fine coloring agents that penetrate the concrete surface in a manner similar to water-based stains to produce pastel colors. Solvent-based dyes produce reds, blues, oranges, yellows and greens in addition to blended colors. It is important to note that dyes are transparent thus cannot cover or mask color variations (Boyer, 2007).

Figure 2.9 Acid-based stains can provide personalized artwork (Palmer Jr., 2007)

- Water-based tinting compounds produces translucent hues that are less rich and varied as chemical stains as shown in Figure 2.10. Favored types include hydrolyzed lithium quartz compounds that penetrate and react with siliceous materials and mineral compounds thus tending to be longer lasting. They should be applied to non-wet properly cured concrete. Tinted colors are generally softer than the mostly deep rich tones of chemical stains (Rodgers, 2004).

Figure 2.10 Water-based stains produce bright uniform colors (Palmer Jr., 2007)

- Polymer stains are color pigments mixed in a resin and applied to concrete that might be considered also as coating that creates opaque color blocking the original look of concrete (Boyer, 2007).

2.3.4 Stamped Concrete

Stamped concrete represents the largest portion of the decorative market. It is available in a variety of designs, patterns and textures due to the use three-dimensional textured tools before the concrete surface has partially set. Rigid and floppy polyurethane stamping mats have largely replaced cast aluminum and plastic platform stamps giving the concrete surface both pattern and texture as shown in Figure 2.11 (Scharich, 2008). The use of stamped concrete is usually coupled with color hardeners and a different color release agent. The color hardener produces textures of finer details while the release agent creates variations of color and highlights the low points of texture. Integral color can also be used with stamped concrete as it allows the concrete surface to be sandblasted or acid-washed to expose the surface fines (Boyer, 2002).

Figure 2.11 Stamping concrete patterns using a "walk-on" technique (Lamm, 2002)

2.3.5 Exposed Aggregate Finishes

Aesthetic effects can be achieved by sandblasting, brushing or washing the concrete surface to remove the cement paste and expose the aggregate. A uniform appearance can be achieved using locally available gap-graded aggregates. Unattractive locally available aggregates can be seeded with colored gravel or crushed stone. This can be done by finishers striking of the surface to reach a depth slightly below the finish level followed by uniform hand distribution and finally embedding with a darby or bullfloat (Boyer, 2002). Other techniques for producing exposed aggregate surfaces include, but not limited to, the following:

Sandblasting: Also known as abrasive blasting is a common method that yields exposed aggregate textures ranging from light, medium to heavy blasting. It is widely used for vertical cast-in-place concrete walls and outdoor flatwork panels. A light sandblast texture results in a sandy surface and is dependent on operator skills. While heavy sandblasting exposes the coarse aggregates in concrete. Another decorative effect can be achieved by combining both techniques to produce “checkerboard” or other patterns in concrete with optional seeding and sawcutting (Al-Anany, 2005).

Wash-off: A technique that removes a thin layer of cement paste by brushing then the surface is flushed with water immediately after concrete has hardened. A chemical surface set-retarder is applied to prevent the matrix hardening at the surface to a specific depth. This can be controlled by the strength of the retarder. The retarder is removed with the retarded outer layer of cement paste carefully after the mortar retaining the aggregate has sufficiently set to prevent dislodgement of aggregate (Al-Anany, 2005).

Acid Etch: A specialized treatment that etches the concrete surface to produce a fine texture by bringing out the full color of the exposed aggregate. Aggregates used should be acid resistant, such as quartz or granite. Limestone, dolomite and marble aggregates would discolor or dissolve with such treatment due to their high calcium content. Commonly used by pre-cast plants, the texture production is performed using hydraulic acid with a percentage ranging between 5 to 35 percent. This is done either by spraying, brushing or immersion of pre-cast concrete units which requires later neutralization with an alkaline bath in addition to flushing with water. Due to hazards of this application, the difficulty of uniform application of acid solution, neutralization and runoff control, acid etching treatment has to be assigned to specialized contractors. It is important to note that acid etch treatment should not be started until concrete has reached a compressive strength of 31 MPa or is 14 days old (Al-Anany, 2005).

High Pressure Water Jet: A more recent technique for exposing aggregates using high pressure water jets combined with air. Pressure used for such water jets ranges between 21 MPa to 69 MPa. Generally it should not be applied before the compressive strength of concrete has reached 10.3 MPa. Application time and curing conditions determine the desired amount of exposure without dislodging the aggregates. This method can be used with or without surface retarders. However exposure should be started immediately after for removal if surface retarders are not used (Al-Anany, 2005).

2.3.6 Overlay Cement

Originally invented as an overlay cement layer for steel ship decks and patented “Plastic Composition” that consisted of natural rubber latex mixed with Portland cement and aggregates. This would provide not only corrosion protection but traction too. Today, polymer resins are mixed with color pigments and cement are sprayed with hopper gun on concrete slabs as shown in Figure 2.12. They are knocked down with trowels in thin 6 mm application. It can also be used for self leveling floors with a thickness between 6 to 13 mm in addition to their use in texturing and stamping creating infinite color possibilities and applications (Nasvik, 2004).

Figure 2.12 Spraying pigmented overlay cement (Tosalt, 2011)

2.3.7 Paper Stencil Patterning

In 1978 Gerald Brasseaux placed a patio in Los Angeles with concrete which set slowly as a result of cold weather. As he waited for finishing the surface tree leaves fell on the fresh concrete giving the idea of paper stencil patterns as a popular decorative concrete technique. A machine was developed to cut stencil patterns in paper. Paper stencils are embedded on the concrete surface after it is placed; a color hardener is applied, floated and finished. After concrete initial set the paper stencils are carefully removed creating different patterns as shown in Figure 2.13. It can also be used with overlay cement for decorating existing slabs on grade (Nasvik, 2004).

Figure 2.13 Stenciling with paper patterns on fresh concrete, applying hardeners then stencils are removed (Nasvik, 2004)

2.3.8 Sandblast Stenciling

Using sandblasting for creating patterns in vertical and horizontal concrete is an old technique that dates to more than seventy years ago. This is a thorough and exhausting technique which led to the development of adhesive plastic sheet templates that are sticked are adhered to concrete surfaces, and then patterns are cut out manually. Complicated design patterns can be applied by cutting templates using precision plotters aided by computers as shown in Figure 2.14 (Nasvik, 2004).

Figure 2.14 Removing parts of computer-cut template before sandblasting the floor for a final stunning look (Nasvik, 2004)

2.3.9 Architectural Walls Form liners

It started as complicated frescos or graphics that were made of plaster and inserted into wall formwork. After concrete is placed the plaster would be broken down to reveal the design, thus the form liner was used only once. Reusable form liners became available using elastomeric urethanes that measured a length of 120 feet and a width of 10 feet. Later form liners were developed of masonry units with random patterns that can be achieved by rotating the unit (Nasvik, 2004).

Figure 2.15 Precast architectural form liners (www.heringinternational.com, 2013)

2.3.10 Concrete Polishing

Warehouse flooring was the first market of this technique. Owners thought of polishing their floors to solve epoxy coatings that tended to lose bonding thus reducing maintenance costs. Developed mainly by the stone surfacing industry, polishing and grinding became a popular demand for concrete floors and countertops. The same diamond abrasive polishing pads and planetary head grinders used to polish stones are applied on concrete. Generally it is a fast process and can result in a smooth finish of 3000 grit compared with 120 grit for terrazzo concrete finish. More decorative possibilities for homes currently use pigmented concrete, embedding objects and then polishing concrete or applying chemical stains at different stages as shown in Figure 2.16. It can also be used for exposing aggregates (Nasvik, 2004).

2.3.11 Decorative Saw Cutting

Originally used to create contraction joints to allow shrinking and cracking of concrete, saw cutting can also be used as an artistic tool to enhance concrete by making decorative joints. This can create a look of individually placed tiles or panels by breaking the large stretch of flat concrete surface. While a contraction joint saw cut depth can reach 25 percent of slab thickness, decorative saw cut is usually 19 mm deep to provide enough shadow with a width between 3 to 5 mm (Boyer, 2002). Single or double circular diamond blades can be used for saw cutting decorative patterns. It is believed double blade cuts are more aesthetically pleasing (Boyer, 2007).

Figure 2.16 A cafeteria concrete floor that was saw-cut in a curved pattern followed by application of different colors of chemically reactive stains and finally polishing to give an attractive new look (Thome and Rizzo, 2004)

2.3.12 Home Decorative Applications

Home interiors can use pigmented concrete in creating a lot of home fixtures thus furnishing home interiors with different, warm and spacious appeal. Decorative concrete made its first appearance indoors as kitchen countertops, then came concrete sinks, floors and tables as shown in Figure 2.17. Concrete countertops thickness ranges from 7 to 15 cm or more. They can have simple or complex shapes in addition to special features as molded drain boards. Other applications include bathroom furniture as sinks and tubs. Some bathrooms are too small to fit in standard components while others can be spacious and require larger pieces. This design issue can be solved using customized decorative concrete fittings. It should be taken in consideration the own weight of large decorative concrete tubs and its effect on the structural safety of the building, especially when filled with water. Other applications include concrete fireplaces, floors, tiles and walls that tend to moderate interior temperatures as concrete tends to absorb heat from sunlight during day and radiates the heat back at night (Huber SUN, 2007).

Figure 2.17 Integral countertops, sinks and bathtubs can be achieved for interior decorative applications (Concrete International, 2007)

2.3.13 Cast-In-Place Wall Caps

When enhanced with pigmented concrete, cast-in-place wall caps can be produced in various shapes and textures. Caps are generally placed on existing masonry or concrete elements to create a cover, seating surface or pool and fountain coping. Standard designs are available but any desired shape can be achieved (Boyer, 2002).

2.3.14 Glass Concrete

It was originally developed as an environmental method for using glass solid waste. This involves using crushed waste glass as coarse and fine aggregate to create glass concrete. One of the concerns was overcoming the alkali-silica reaction (ASR) between glass and cement (Abou Alia, 2007). Glass concrete specialists acknowledge the problem but argue that not a single case was tackled during their practice (Nasvik, 2006). Other investigations involved the addition of Metakaolin (MK) with recycled fine glass aggregate and white cement to mitigate alkali-silica reaction resulting in effective suppression of ASR expansion in addition to increasing the resistance to acid attack (Ling et al. 2011). Recycled glass used must not be contaminated to be used in concrete, recycled glass bottles are not a usable source for glass concrete. Recycled glass is generally long and flat in shape thus it cannot be used as aggregate in concrete as the best for use is cubical shape. Thus, glass aggregate supply companies collect refuse glass from product manufacturers of windows, mirrors and bottles. It is sorted according to its color then it is melted and crushed. Afterwards it is sorted by size and sharp aggregates are dulled. Size ranges from fine aggregates to 10 inch diameters. Glass aggregate can be supplied in twenty different colors, with red and orange as the most expensive (Nasvik, 2006). It is possible to replace white cement in architectural concrete with fine recycled glass aggregate. This improved the performance, workability and drying shrinkage of the cement mortar (Ling et al. 2011). Glass fine aggregates alter the concrete mix design since it has zero water absorption, thus increasing concrete durability (Abou Alia, 2007). Glass aggregates can be used for decorative concrete for a variety of decorative finishes as shown in Figure 2.18. Decorative finishes may include exposed aggregate, sandblasting and stencil patterning. They are often broadcast on fresh concrete surfaces of countertops and floors and then a final finish of diamond polish is applied (Nasvik, 2006).

Figure 2.18 Hand painted glass inlays that glow with black light illumination (Concrete International, 2007)

2.3.15 Light Transmitting Concrete

Among variable properties of concrete opacity was always unquestionable. But in the 21st century, innovative trials were conducted to create light transmitting concrete, LTC. Two theories were proposed to produce LTC. Theory of Concrete Components Substitutes involves analyzing and replacing concrete ingredients with translucent and transparent alternatives. The second theory is to use embedded light transmitting material while casting concrete such as optical fibers that serve as a light carrying media, "Theory of Doping Light Transmitting Material" (Abou Alia, 2007).

Theory of Concrete Components Substitutes

The methodology for this theory includes breaking down all the traditional concrete ingredients and finding alternative materials that posses light transmitting properties. Several trials were conducted. First trial was called Pixel trial panels and involved substitution of aggregates with crushed glass, cement by polymer and reinforcement by translucent reinforcing plastic. This material is suitable for construction applications including columns, panels in addition to decorative applications like bathtubs, tables and lamps. Another trial was done using translucent and mega pure epoxy as two types of binder and crushed waste glass as a substitute for aggregate. Light testing showed that maximum thickness required for light to pass through should range between 30 to 60 mm. However, light transmitting properties decreased with increasing epoxy percentage in the mixture (Abou Alia, 2007).

Theory of Doping Light Transmitting Material

Additional light transmitting material is embedded into conventional opaque concrete to create a light transmitting medium inside the matrix. Several methods can be used to achieve. Sensitile is a patent for tiles and panels containing light pipes and optical fibers that react to changing light intensities. Light falling on these panels will be reconfigured, redirected and scattered producing a set of ripples at the surface. Light source quality is an important element affecting the final performance. Litracon is another application invented in 2001 by Aron Losonczi. It uses embedded optical fibers that run parallel to each other in the conventional concrete mix. Light rays pass through the fibers starting from the illuminated exterior and are guided inside the core by internal reflection till they exit at the interior side as shown in Figure 2.19 (Abou Alia, 2007).

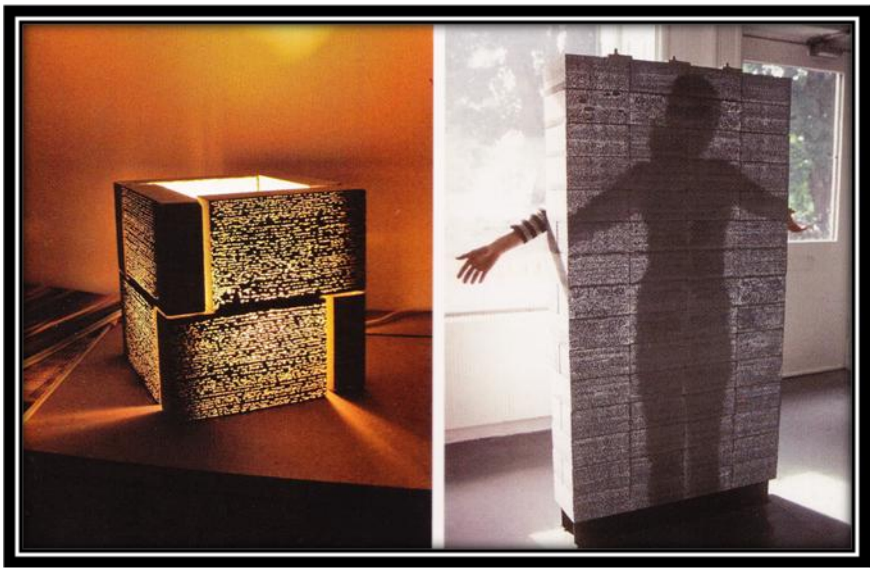

Figure 2.19 Light rays passing through concrete embedded with optical fibers (Huber SUN, 2007)

2.3.16 Photo-engraved Concrete

A process that involves a high degree of etching that produces photos on concrete surface with a soft relief. It was created first produced by Pieri, a French chemical company and was named photo-engraved concrete. The first prototype was precast façade panels done at a library in Jura, France in 1986. The manufacturing process starts by applying a liquid set-retarder on the reversed overprint form plate, or the photo negative plate is fixed on panel form when applying to concrete panels. Self-compacting concrete is used to purge using of concrete vibrators that may cause photo damage. Concrete is mixed, poured and placed and plates are removed after twenty four hours of curing. The retarded part of the surface paste is removed with water jet.

Finally, a dark wet concrete photo starts appearing and gains different color while drying as shown in Figure 2.20 (Abou Alia, 2007).

Figure 2.20 Precast photo-engraved concrete panels (www.heringinternational.com, 2013)

2.4 Pigmented Concrete

Portland cement was named after the cream colored stone that it bears a resemblance with, which was quarried in Portland, England. From the very beginning concrete had been providing a white or grey background that neutrally reacts with light and shadow. Though the use of concrete with this approach helped manifest architectural design to an abstract form, but it failed to satisfy contemporary architects who preferred the creative use of color and versatile surface treatments. As a result, the interest in concrete color and texture has significantly increased in the last decade. The production of inorganic iron oxide pigments has reached about 1 m tons in 2010 worldwide with construction materials accountable for 48 percent of consumption (IHS, 2011).

2.4.1 Pigmented Concrete Materials

High demand is placed on concrete surface especially when it is fair-faced or pigmented concrete. A noticeable difference can be distinguished between the aesthetic looks of a synthetic surface and those of natural surfaces. Under influence of modern design in car industry, ceramics, synthetic and metal surfaces customers' expectations about precision and homogeneity are maximized. On the other hand natural surfaces such as stone are expected to be unique. Pigmented concrete surfaces are often associated with synthetic materials without taking into account that it is made of natural raw materials. As a response, pigmented concrete manufacturers always demand their suppliers to deliver raw materials with constant color, quality as well as trying to standardize the whole process and recipes. Nevertheless slight fluctuations in natural color and quantities added for cement, aggregate, pigment and water resulting in changes in color may occur (Weber et al. 2009).

2.4.2 Cement

Cement is the primary ingredient in concrete; its color is the governing factor for the pigmented concrete. Variations in color of cement will occur even within the same brand over time due to the fluctuations in mining, manufacturing and blending operations. Thus it is recommended to use the same type, brand and strength class of cement. Weber et al studied the effect of two grey cement types of similar class 42.5 can result in slight color difference when pigments are used due to difference in Blaine values. Finer cement will be pigmented less than coarser cement (Weber et al. 2009). Since Pigment only colors the cement paste, the increase in cement fineness may lead to loss of color consistency since the pigment has to cover a larger surface area of cement particles (NCMA, 2002). Generally cement used for pigmented concrete should meet the requirements of ASTM C150, ASTM C 595, ASTM C 845 in addition to other standards (ACI 303.1-98). Cement used for pigmented concrete can be grey, white or colored. Colored cements are not widely available and limited in color choices thus it is recommended to check for their availability before making a color selection. To achieve best results for projects that require pigmented concrete it is advisable to use white cement. White portland cement is manufactured from raw materials containing negligible amounts of iron oxide (less than 0.3 percent by mass of clinker) and magnesium oxide that mainly produce grey color. White cement is more expensive due to the higher cost of its clinker grinding process that mainly aims to avoid cement contamination with iron in addition to higher cost of raw materials. White cements have different inherent color characteristics depending on impurities. It can have faint green or yellow hue. Traces of chromium cause the greenish hue, while magnesium traces cause a bluish-green hue and iron traces cause yellowish hue. Thus care must be taken when using white cement to produce pigmented concrete as discolorations might occur. While the cement content in the mix might be small compared with the aggregate, white cement has a remarkable influence on the color of the finished product. Regarding properties of white cement, it has a slightly lower specific gravity than ordinary Portland cement, has higher fineness in order to increase the brightness of white color and its strength is somewhat less than that of ordinary Portland cement though it complies with requirements of BS 12:1991. A typical composition of white cement may contain 1 percent of C_4AF which may lead to lower 7-day compressive strength (Neville, 2011). An investigation performed at Suez Canal University resulted in 30 to 40 percent decrease of 28-day compressive strength of pigmented white concrete mixtures compared with grey unpigmented concrete (El-Awadly, 2012). Grey ordinary Portland cement may limit the color range for pigmented concrete. The most common color worldwide is medium grey and it's the base for color charts for almost all color-conditioning admixtures. Due to its tinting effect on pigmented concrete cement of the same type and brand should be used per project to minimize color variations (Weber et al. 2009). Grey cements are recommended for producing darker colors or earth tones but not advisable if light or buff tones are desired. They can also be lightened by adding titanium dioxide (NCMA, 2002).

2.4.3 Pigments

Pigments are powders that pass through sieve No. 200 and the shape of particles for each individual pigment has a considerable effect on strength, workability, drying shrinkage and the durability of cement composites (Lee et al. 2004). Pigments include untreated mineral iron oxide which is similar to iron rust and occurs in red, yellow and orange colors in addition to chromium oxide green, cobalt blue, titanium dioxide white and carbon black (Paris and Chusid, 1999). Mineral pigments are used when color uniformity of concrete product is not critical such as interlocking pavers, concrete blocks and roof tiles (Hodson and Kushner, 1992). More intense and consistent colors are produced from synthetic pigments which are finely interground, chemically inorganic, ultra violet fade resistant and environmentally friendly pigments (Paris and Chusid, 1999). An investigation was performed to compare the effect of synthetic and mineral iron oxide pigment on properties of interlocking blocks showed better performance of mechanical properties and color stability of synthetic pigment (Lee et al. 2003). Pigments are used as admixture in concrete for producing pigmented concrete when used as powder or granules in the concrete matrix or can be a constituent of a multi-component admixture commonly known as pigment slurry (NCMA, 2002).

Figure 2.21 Inorganic pigments are finely interground particles produced in a variety of colors (Lanxess.com, 2013)

General Pigment Properties

- **Wettability and Solubility** Pigments should be easily water wettable so that it would disperse uniformly in the mix and will not leach on concrete surface due to weathering (ASTM, 1981). Pigments should also be water soluble with soluble matter that does not exceed 2.0 mass % of the original pigment sample tested (ASTM C979/C979M, 2011). Insolubility is a mandatory property for color durability in the final concrete product (NCMA, 2002).
- **Atmospheric Curing Stability** Pigments should be able to keep their color during concrete curing (ASTM, 1981). The magnitude of color differences between pigmented concrete specimens cured in dry air and other specimens cured at high relative humidity shall not be greater than color difference between unpigmented concrete specimens cured under similar conditions (ASTM C979/C979M, 2011).

- **Alkali Resistance** Pigments should be alkali resistant showing no change of color when exposed to sodium hydroxide and cement hydration (ASTM C979/C979M, 2011).
- **Total Sulfates** Pigments should have a sulfate content (calculated as SO_3) that does not exceed 5.0 percent by mass of the original pigment sample tested (ASTM C979/C979M, 2011).
- **Light Resistance** Pigments that show difference in color between exposed and unexposed surfaces when tested with Type E or EH light exposure apparatus are not considered light resistant. Pigments that pass light resistance testing may still be subject to fading when directed to natural weathering conditions (ASTM C979/C979M, 2011).

Pigment Content in Concrete

Pigment dosage prescribed rate shall not exceed 10 percent by weight of cement in a specified concrete mix. Pigment expands the surface area of cement when added to concrete resulting in decreased workability. An investigation done on three types of pigments, iron oxide red, yellow and chromium oxide green added to mortars has shown that compared with standard non-pigmented mortar, the flow of red iron oxide pigment mortar decreased as the ratio of used pigment increased. While in case of yellow iron oxide pigment a rapid decrease in flow occurred. It was concluded that the needle shaped particles of the yellow pigment have larger surface area than the spherical shaped particles of the red pigment causing the rapid decline in mortar fluidity as shown in Figure 2.22 and Figure 2.23. On the other hand, green chromium oxide synthetic pigment; also spherical in shape resulted in better mortar flow with addition of 3 percent and 6 percent of pigment. Minor decrease in mortar flow as the ratio of used pigment increased to 9 percent and 12 percent. This is attributed to the larger diameter of spherical particles of the green pigment shown in Figure 2.24. This leads to the creation of repulsive forces between the particles caused by chromium oxide acting as the main ingredient (Lee et al. 2004). Accordingly, water content in the mix should be adjusted depending on the pigment color, particle size and shape with a maximum additional water of 10 percent more than the control mix (Neville, 2011). Another study has concluded that the addition of Ultramarine blue inorganic pigment increase the 7-day compressive strength of concrete made with white cement. It has shown an increase of compressive strength at 90-day when 15 and 20 percent of pigment were added compared to control mix. Ultramarine blue consists of silicate aluminum complex with sodium and sulphur. One possible hypothesis is that ultramarine blue pigment reacts directly with calcium hydroxide free in the hydration of Portland cement behaving like natural pozzolans by forming a complex of aluminum, calcium and silicon. Mineralogical analysis at 7-day show that primary ettringite formations increase in quantity as the pigment percentage increases in the mix. This is attributed to the possible reaction between the sulphur content in the pigment with the tricalcium aluminate C_3A present in white cement in the presence of water. This implies that ultramarine blue pigment can substitute cement in the mix even though it was verified that pigment does not exhibit pozzolanic effect (Gutierrez et al. 2009).

The Saturation Curve

Increasing pigment amounts in concrete increases the color intensity. Usually the increase in color is not linear with the increase in amount of pigment. Instead, the increase in color intensity follows a curve (Weber et al. 2009). On pigmenting a

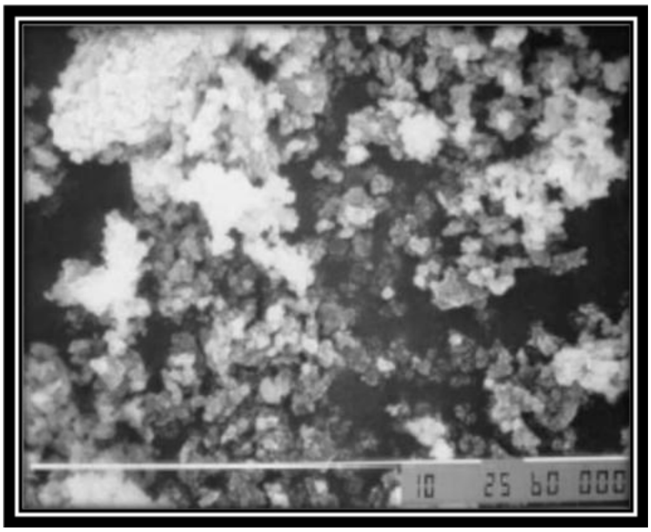

Figure 2.22 SEM picture of red pigment (Lee et al. 2004)

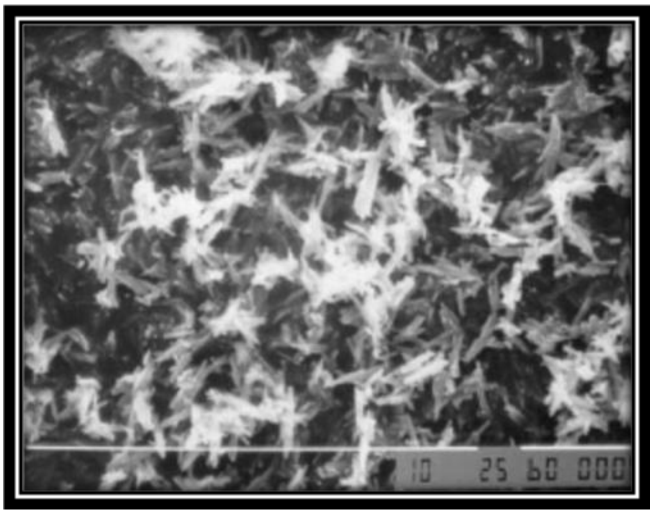

Figure 2.23 SEM picture of yellow pigment (Lee et al. 2004)

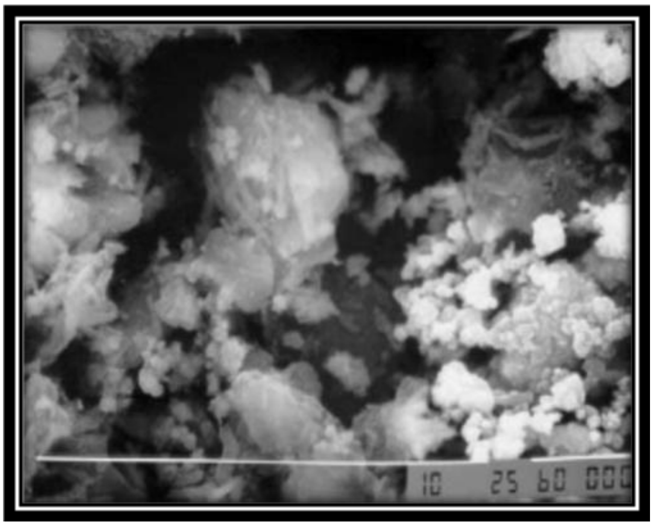

Figure 2.24 SEM picture of green pigment (Lee et al. 2004)

concrete product, when increasing the pigment dosage fails to make a noticeable difference in the color intensity. This is known as saturation point. Most color shades can be achieved with dosage rates below 7 percent. Black iron oxide has a high tinting strength and achieves saturation at 6 to 7 percent dosage. Brown and red iron oxides have slightly less tinting strength reaching saturation between dosages of 7 to 8 percent. Yellow is considered to have a low tinting strength reaching saturation around a dosage of 9 percent (NCMA, 2002). It is important to note that at 7 days pigmented concrete appears brighter and more intense. By the age of 28 days and in ambient temperatures about 85 percent of mechanical properties are achieved but concrete still contains hydration water rendering its surface darker. Thus, pigment tinting strength should be assessed at 28 days. Chromatic color assessment conducted on pigmented red and yellow concrete with 6 percent dosage show that color values stabilized after 48 days (Positieri and Helene, 2008).

Pigment Effect on Concrete Properties

Compressive Strength Pigmented Concrete that uses the maximum prescribed pigment dosage shall have a 28-day compressive strength of no less than 90% than that of the control mix (ASTM C979/C979M, 2011). Corinaldesi et al recorded slight decrease of 3 percent at 28-day compressive strength when pigments were incorporated (Corinaldesi et al. 2012). Another investigation resulted in 28-day compressive strength reduction between 2 and 9 percent (El-Awadly, 2012).

Water-Cement Ratio Pigmented Concrete should have a water-cement ratio of no more than 110% than that of the control mix (ASTM C979/C979M, 2011).

Setting Time Pigmented Concrete that uses the maximum prescribed pigment dosage shall not accelerate the initial or final set by more than 1 hour. It also shall not retard the initial or final set by more than 1.5 hours when compared with non pigmented concrete mix (ASTM C979/C979M, 2011).

Air-Entraining Pigmented Concrete that uses the maximum prescribed pigment dosage shall not change the air content by more than 1% compared with unpigmeneted control mix with an equal quantity of air-entraining admixture used (ASTM C979/C979M, 2011).

2.4.4 Aggregates

Aggregates selected for pigmented concrete should be selected carefully as they may contain minerals of iron base that may cause stains when in contact with the atmosphere (ACI 303.1-98). The color of coarse aggregate is not usually a significant factor for pigmented concrete unless an exposed aggregate finish is specified. Generally all aggregates should comply with ASTM C 33 and must be clean and free from clay, mineral dust and organic impurities (Hodson and Kushner, 1992). Fine aggregates affect the pigmented concrete in the same way as cement. Since fines are blended with cement and water to form mortar that determines the color of concrete surface thus they can also cause different concrete pigmentations. The relationship between cement paste surface and the fine aggregate surface will change as different fines are used which would influence the final appearance of pigmented concrete surface. This may also result in different tinting strength for light colored pigments. Grading must also be chosen carefully for the desired surface finish of concrete (Weber et al. 2009). Some fine aggregates may contain residual dust that is darker in color and may not be removed by washing. Fines containing such dust may change the resulting color of pigmented concrete. Also some darker grains may become exposed with wear causing the concrete surface to appear darker (Hodson and Kushner, 1992).

2.4.5 Admixtures

Admixtures used for pigmented concrete are water reducing and set controlling that conforms to requirements of ASTM C 494. Air-entraining admixtures should conform to requirements of ASTM C 260. However it is extremely important to verify the compatibility of any admixture to be used with any pigment. Major pigment producers specify compatible admixtures. Any admixture containing calcium chloride shall not be used with pigmented concrete to minimize efflorescence. Liquid coloring admixtures consist of synthetic pigments mixed with water reducing admixtures that improve the workability and finishing characteristics of concrete. This also facilitates the dispersion of color within concrete usually through computerized dispensing systems used at concrete batching plants. This has lead to improved concrete color consistency and accuracy in addition to increased concrete strength and reduced efflorescence (Hodson and Kushner, 1992).

2.4.6 Water

Municipal waters are mostly satisfactory for use in pigmented concrete. However it is always recommended to test water obtained from other sources like wells or shallow ground water for presence of salts or iron compounds. This minimizes efflorescence and staining respectively. It is important to note that using slurry of water and pigment is not recommended. Adding 100 percent powdered pigment directly to the concrete mix improves dispersion and hence the consistency of pigmented concrete since slurries usually contain 60 to 70 percent of pigment added to 30 to 40 percent of water (Lanxess.com, 2013).

2.4.7 Water-Cement Ratio

Water-cement ratio is a governing effect in producing pigmented concrete. Differences in water-cement ratio are one of the major causes of varying color hues and lightness on the surface of concrete. As water-cement ratio is increased leads to a lighter color surface. As water content increases in the mix, liquid consistency for the hardened cement paste increases. This leads to more cement paste penetrating to the surface during compaction resulting in a smoother surface with less light-absorbing pores. In addition, higher water content may lead to the formation of finer branching needles of cement at the concrete surface resulting in light diffusion. It is important to maintain the same water-cement ratio on different placements to produce a uniform color (Weber et al. 2009). Chromatic color assessment conducted on pigmented red and yellow concrete with w/c ratios 0.46, 0.56 and 0.65 resulted in slight to almost no effect on final color (Positieri and Helene, 2008).

2.5 Color and Colorimetry

2.5.1 Seeing Colors

According to the Penguin Dictionary of Physics (2009), Colorimetry is defined as "The science that aims at specifying and reproducing colors as a result of measurement". Light is a narrow band of energy radiating from the sun that can be divided in a group of colors called spectrum. Colors of the spectrum vary in wavelength with a visible range extending between 400 to 750 nanometres. In 1665, Newton demonstrated that white light can be obtained using a second prism when all spectrum colors are combined. In 1807, Thomas Young found out that white light can be obtained mixing red, green and blue beams only while all other colors can be obtained by mixing these three colors in different proportions. This became the basis of the theory of vision later developed in 1856 by Helmholtz known as the Trichromatic theory of color vision. Three factors determine how humans perceive color; the light source, the surface of the object and the observer himself. To measure light radiation a standard source called "black body" is used. It consists of a small furnace that can be heated to reach different temperatures. At about 500 degrees Celsius it becomes "red hot" and becomes increasingly white as it reaches 6000 degrees Celsius (equivalent to the surface temperature of the sun). Thus artificial or natural light can be expressed in terms of "color temperature" (Porter and Mikellides, 2009). The Commission Internationale de L'Eclairage (CIE) defines several standard light sources. As an example, reference illuminant D50 has a correlated 5000 K color temperature which is used to compute L*a*b* data in Adobe Photoshop and is the only illuminant used as a link between devices in Profile Connection Space (PCS) set as a profile definition by International Color Consortium (ICC) (Pascale, 2003).

2.5.2 Color Attributes

Color is split into three factors; Hue (or tint), Saturation, Lightness (or luminance). Hue is the characteristic or quality by which one color is distinguishable from another. Elementary hues that can be differentiated are spectral ones; red, green, blue, yellow, orange and violet. All colors are judged to be similar to one or a proportion of two spectral hues. Hues are physically determined by wavelength. Since white, grey and black are perceived as colorless, their lack of color (chroma) causes them to be termed achromatic. Saturation is the second distinguishable attribute of color. It designates the purity of a color separating it from weaker or greyed color. It can also be referred to as intensity, strength or chroma. Two colors can have the same hue, and not lighter or darker than one another yet have different appearance in color strength. Lightness (or luminance) is the third dimension of color that differentiates a dark from light color. Lightness of a pigment is a measure of how much light is reflected from its surface (Mahnke, 1996). These three attributes are the base for the universal systems of color defining set by CIE (Lemaire et al. 2005).

2.5.3 Color Systems and Measurement

Anyone working professionally with color will find it crucial to use some kind of color classification system. In these systems, colors are listed by hue, saturation and lightness. Colors are also presented in sequence and in their relation to one another. Other models are composed of color chips and patches for visual matching are developed to help human selection of colors, Munsell system and Natural Color System (NCS) are an example (Mahnke, 1996). CIE has devised color systems presented in mathematical form and based on spectrophotometric measurements for color samples which are most accurate but inconvenient for everyday practical use. Spectrophotometers or colorimeters are computerized color measurement instruments that cast a light source at the surface of object or sample under evaluation. Depending on sample color certain wavelengths are absorbed while others are reflected back and computed by the device that converts them into numerical values. Those values are mathematically compared to a standard reference stored in the device (NCMA, 2002). The preset measured area ranges between 25 mm^2 to 10 mm^2 (Lollini and Bertolini, 2013).

Munsell System

Munsell system of color notation is the universal system for selecting and communicating color that was developed at the beginning of the twentieth century to overcome vague nomenclature of color (Linton, 1999). It is based on the Munsell color wheel shown in Figure 2.25, which incorporates three basic color criteria: how a specific color stands in relation with others; how will it look when subjected to lightness or darkness and how it will look when changed in its strength or weakness. Munsell colors are identified using the three attributes of color: hue, value (lightness) and chroma (saturation). In his color space, Munsell conceived five major hues arranged in a circle or wheel, from red (R) to yellow (Y) to green (G) to blue (B) to purple (P) and back to red. Between these five intermediate colors are identified: yellow-red (YR), green-yellow (GY), blue-green (BG), purple-blue (PB) and red-purple (RP). The second dimension of the Munsell system is value or the degree of lightness or darkness of color in relation to a neutral scale. The scale starts from value symbol 0 (absolute black) to value symbol 10 (absolute white) while symbol 5 designates the middle value of grey for all chromatic colors. The third notation is chroma indicating the strength or purity of color (Mahnke, 1996).

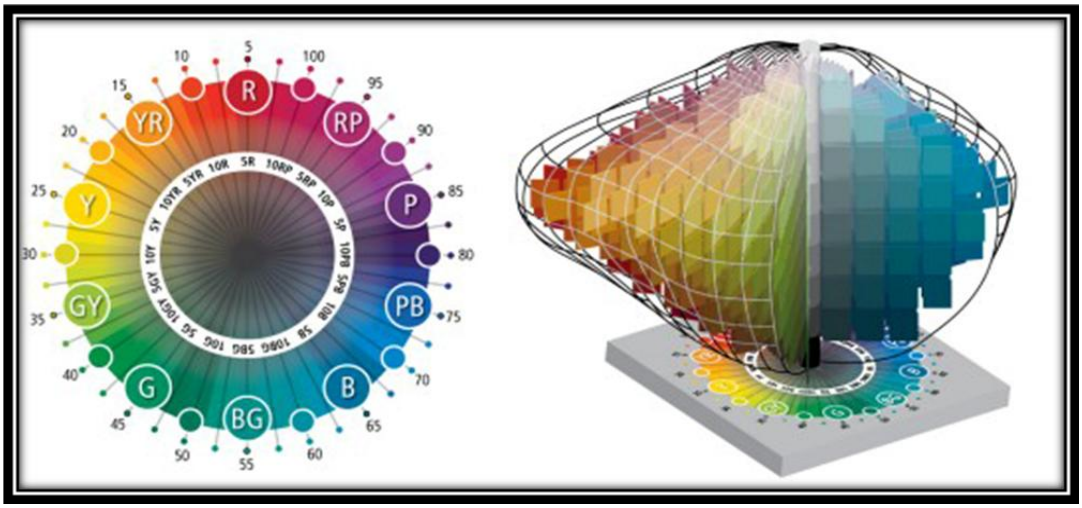

Figure 2.25 Munsell color system (munsell.com, 2013)

Natural Color System (NCS)

This process was devised by Ewald Hering in 1874 and has been under development and experimentation since 1964. Psychological research and experimental work were conducted aiming at the discovery of the degree to which people are capable of quantifying color perceptions in terms of NCS. Finally, the NCS Color Atlas was presented and scaled in order. With six suggested elementary color experiences: white (W), black (S), yellow (Y), red (R), blue (B) and green (G). All other colors are related to these elementary colors with various degrees of similarity. All these relationships are represented in a three dimensional color space and its two dimensional projections; the color circle and the color triangle as shown in Figure 2.26. In the NCS designation 2030-Y90R for example, 2030 indicates the nuance or the degree of resemblance to black (S) and to the maximum chromaticness (C), in this case, 20 percent blackness and 30 percent chromaticness. The hue Y90R indicates the percentage of resemblance of this color to two elementary colors, in this case yellow (Y) and red (R). Y90R means yellow with 90 percent redness. Purely grey colors lack color hue and thus are given notations followed by N (as neutral) (Porter and Mikellides, 2009).

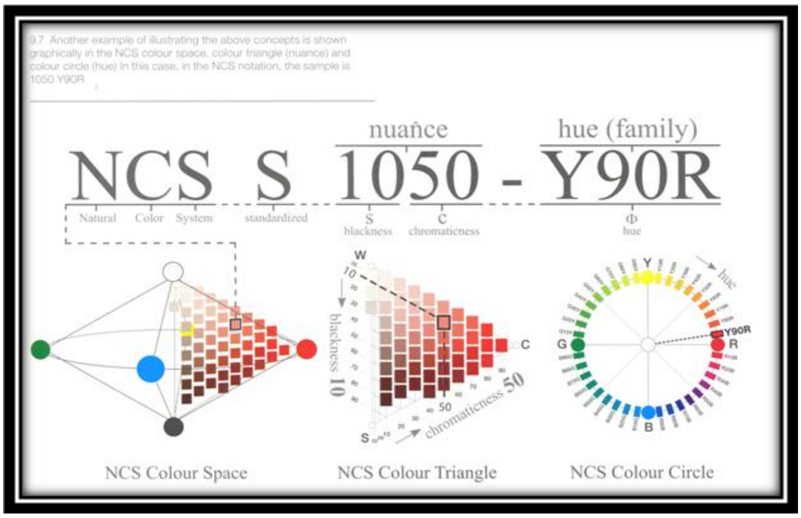

Figure 2.26 NCS color system (Porter and Mikellides, 2009)

2.6 Mathematical Color Spaces

Those are color spaces devised to ease computerized data processing with tri-coordinate spaces. RGB (Red-Green-Blue) and L*a*b* for instance are three variables enough to describe all colors. Device dependent color spaces will have different coordinates for the same color with different output media. A color RGB value from an Apple Macintosh output is not identical with the same color value from a Windows output. Thus using RGB space requires mentioning the image generating environment i.e. the operating system, display, software and printer. It is possible though to standardize device specific RGB coordinates to standard spaces or vice versa (Pascale, 2003).

2.6.1 L*a*b* Color Space

In CIE's L*a*b* color space, L* represents lightness with values between black (0) and white (+100), while a* represents chromatic value of magenta/red (+127) and green (-128) and b* represents chromatic value of yellow (+127) and blue (-128) (Margulis, 2002). Every color can be clearly defined by these three values and can be input into the color space formed by the three axes L, a and b as shown in Figure 2.27. Differences in color can be specified as the Euclidian distance between two points in color space (ΔE*) and is given by Eq. 2.1. (C*) color saturation can be calculated by Eq. 2.2 (Lollini and Bertolini, 2013; Lopez et al. 2009; Positieri and Helene, 2008).

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad \text{Eq. 2.1}$$

The parameter (C*) is related to color purity represented by a vector from the center to a point in a*- b* plane and can adopt any position according with hue angle (h*) indicating color variance from red, yellow, green and blue at angles 0^0, 90^0, 180^0 and 270^0 respectively or at intermediate values and can be calculated by Eq. 2.3 (Lopez et al. 2009).

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad \text{Eq. 2.2}$$

$$h^* = \arctg (b^*/a^*) \qquad \text{Eq. 2.3}$$

(ΔE^*) is related to visual assessment i.e. human perception capabilities. A (ΔE^*) value between 0.5 and 1.5 indicates slight difference in color hue. A value of 1.5 – 3.0 is an obvious difference, 3.0 – 6.0 is a very obvious difference and above 6.0 is a large difference (Lopez et al. 2009).

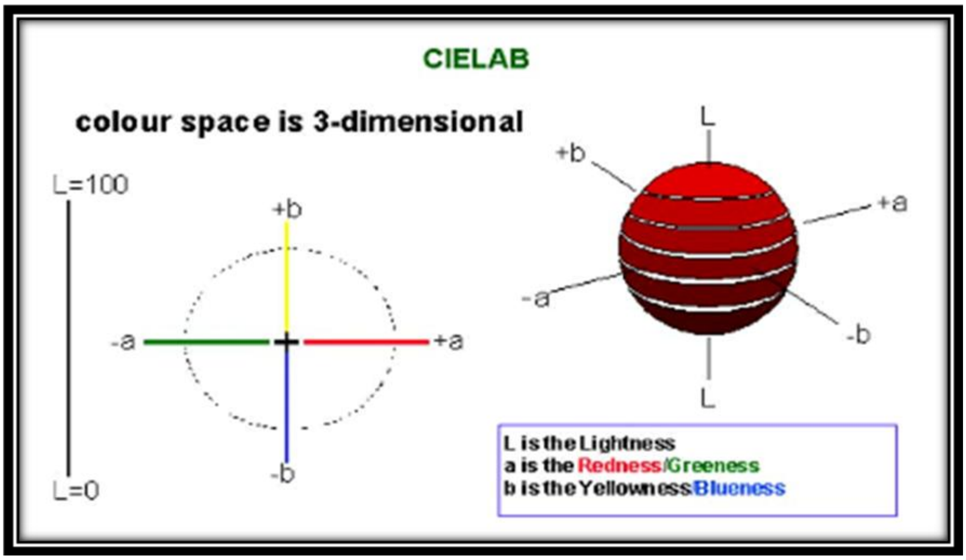

Figure 2.27 CIELAB or L*a*b* color space (Lemaire et al. 2005)

2.6.2 RGB Color Spaces

Any color can be defined in terms of its red, green and blue components in only one way. Every color is unique that no other combination of red, blue and green light can produce it (Margulis, 2002). RGB color space is used in most capturing, printing and displaying devices such as scanners and digital cameras. RGB is non-linear and device dependant producing different RGB values on different devices. However, several caliberation methods are available to transform RGB space into standard color spaces (Annerel and Taerwe, 2011). Three sources or primaries when mixed together in various proportions will generate all colors within a triangular shape that is also called color gamut as shown in Figure 2.28. There is no need to define a large gamut if the number of possible colors is limited. RGB spaces include different spaces, for example Adobe RGB (1998), sRGB, ColorMatch RGB and Apple RGB. These can be handled using a computer software embedded with color calibration profiles, Adobe Photoshop as an example (Pascale, 2003).

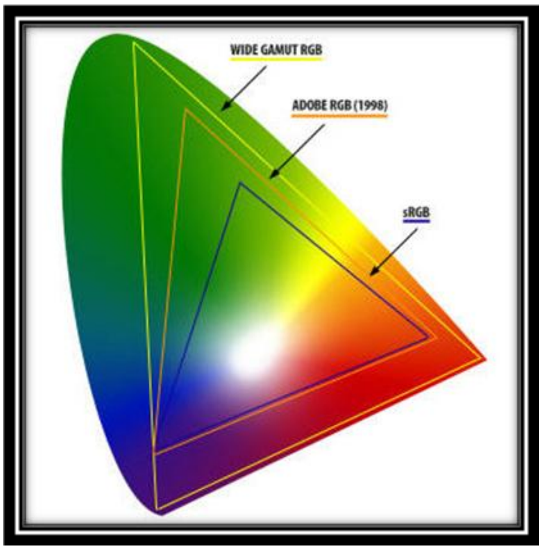

Figure 2.28 Different color gamuts (Pascale, 2003)

2.7 Image Analysis of Concrete Surfaces

Image analysis has become a powerful tool to obtain measurements of size, dispersion, shape or components of cement and concrete materials. With the developing progress in image acquisition tools, software and new algorithms image analysis has become the only way civil engineering scientists can use to obtain statistical information on homogeneity and dispersion (Chermant, 2001). Midrange and professional digital cameras can capture images in RAW format. A RAW file represents unprocessed data captured by the image sensor in the camera and is typically several times larger than an equivalent JPEG file. Shooting in RAW format captures a wider range of color and a more accurate image detail thus more information are contained in a RAW file. A RAW file may contain more than a billion possible colors, 64-times of a 16 million color photograph. Professional image software like Adobe Photoshop Creative Suite may be used to round-up or distill these billion colors down to the best 16 million and this process is called camera RAW correction. Photoshop software supports RAW files from select group of digital cameras including Nikon and Canon. RAW camera files end with suffix NEF for Nikon and CRW for Canon (Mcclelland, 2004). Color coding of digital images also depends mainly on illumination conditions of photographed object and the automatic algorithm system of each camera manufacturer. Thus a standard illuminant defined by CIE standards should be used in capturing all concrete surface images required for evaluation. Architects and building owners have strict requirements with the concrete surfaces that are mainly concerned with tint. Thus techniques must be established for concrete surface evaluation. Concrete surface measurements may consist of simple visual comparison of the surface printed in grey scale of seven levels, level one being the lighter and level seven is the darker. This method might be problematic for some reasons including variations in printing scale from the standard and different optical properties between concrete and paper. In addition subjectivity of human eye and the lightness variation of seven levels is not linear as shown in Figure 2.29 (Lemaire et al. 2005).

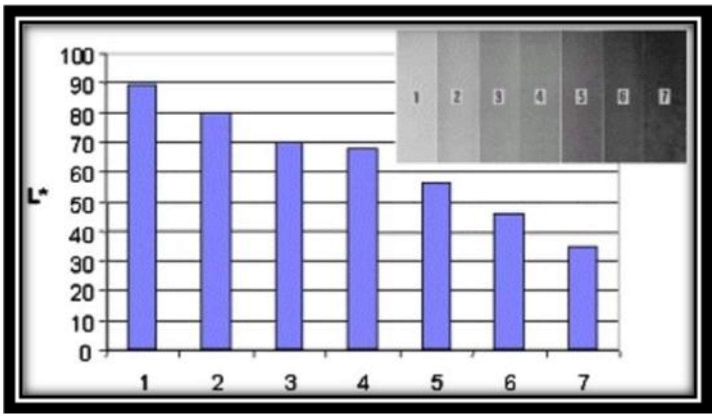

Figure 2.29 Non-linear luminosity values of grey scale levels (Lemaire et al. 2005)

A spectrophotoimeter can be used to measure the color components of concrete surface at several points to give objective results in terms of lightness, hue and saturation. Several investigations were done using this method to acquire L*a*b* values of concrete surfaces; color assessment for structural colored concrete (Positieri and Helene, 2008), quantifying color development of concrete exposed to fire (Annerel and Taerwe, 2011) and color loss of concrete paving blocks (Lollini & Bertolini, 2013). But this method provides information for a few centimeters that do not allow conclusive results about larger square meter surfaces. Thus to analyze a larger concrete surface it is important to acquire color information at all points using one or more images captured with a digital camera. Lemaire et al suggested a technique that enables color homogeneity assessment of concrete surface in addition to a set of measurements to be obtained to characterize the surface regardless the lighting conditions and/or the type of camera resulting in the ability of comparing all pictures. This is done using a corrective process that takes in account type of camera and lighting using a mathematical model (Lemaire et al. 2005). A study on the surface color of sewage sludge mortar used digital imaging technique to acquire RGB values for samples under test (Luo and Lin, 2007). Annerel and Taerwe scanned concrete samples under investigation using a calibrated flatbed scanner as an alternative method of acquiring RGB color information (Annerel and Taerwe, 2011).

2.8 Structural Considerations

2.8.1 Efflorescence

Efflorescence is the term describing the white deposits having an irregular shape on the concrete surface. Efflorescence can be distinguished depending on the concrete age when it appears. Primary efflorescence occurs during setting and early age concrete due to the migration of soluble salts present in cement to the surface of concrete where it precipitates and reacts with carbon dioxide. The main soluble salt is calcium hydroxide. Secondary efflorescence is caused by water travelling through the concrete to the surface at later ages (Neville, 2003). Efflorescence does not represent a structural problem but its presence is undesirable due to its fading of surface color in addition to its non-uniformity (Paris and Chusid, 1999). Measures for prevention or minimization of efflorescence may include thorough washing of aggregates, mixing concrete with lower water content, using admixtures to reduce efflorescence and applying proper curing and sealing techniques for pigmented concrete. Less efflorescence can be achieved by less permeable concrete. Preventing water containing dissolved salts from flowing unnecessarily through concrete or over its surface and proper drainage of rain water away from pigmented concrete elements would limit later formation of efflorescence. Using white Portland cement produces less or no efflorescence due to its very low alkali content (Neville, 2003). Efflorescence is nearly impossible to remove, diamond grinding and sand blasting are efficient removal methods (Nasvik, 2010). Partial removal by dry-brushing followed by water flashing can be applied. Chemical efflorescence removers may be applied to remove stubborn deposits (Nasvik, 2010).

Figure 2.30 Effect of Efflorescence on Pigmented Concrete (Lanxess.com, 2013)

2.8.2 Weathering and Erosion

Appearance of pigmented concrete may change over time due to the wearing away of its surface. When concrete is a new, pigmented cement paste coats grains of fine and coarse aggregates showing the overall pigmented concrete color. As the pigmented cement paste erodes or wears, aggregates become visible at the surface affecting the overall appearance of concrete surface color and texture although pigment is not fading or changing. The more the natural aggregate color contrast to cement paste color, the more shift in concrete surface color due to erosion. Horizontal applications subjected to heavy vehicular traffic and flowing water should have higher cement ratios, higher densities and lower absorption. Vertical applications are more exposed to winds and loose materials that may sandblast the surface. Both applications are subjected to UV exposure (NCMA, 2002). It is recommended that specifiers evaluate the weathered as well as the colored appearance of pigmented concrete (Paris and Chusid, 1999).

2.8.3 Spalling and Cracking

Spalling is mainly caused by poorly designed or constructed joints that affects or permits linear or rotational movements of the structure. Points with higher loads cause structural spalling mainly at joints. Cracking is a major problem that affects the final finished surface of architectural concrete. Cracks can be caused due to different reasons including drying shrinkage, creep, loads, high water-cement ratio and thermal stresses. Cracks can be reduced by several measures including the use of shrinkage compensating cements, post tensioning and using joints for stress relief (ACI 303.1-98).

2.8.4 Joints

Joints ensure the separation of adjacent construction members allowing each to move independently. They have several roles including easing construction and separating different masses, volumes or segments of structures. Controlled jointing is particularly required for walls and roofs to regulate cracking and separation (ACI 303.1-98).

2.9 Quality Control Considerations

Pigmented concrete generally requires a thorough evaluation of materials, equipment and techniques used for mixing, forming, placing, finishing and curing that are required to achieve quality architectural concrete. While numerous types of aesthetically pleasing durable finishes can be achieved with pigmented concrete, the problems mostly encountered are due to improper methods used in handling pigmented concrete (Bell, 1996).

2.9.1 Formwork Considerations

Formwork Materials

Forms can be all wood, wood backed with thin plastic liners, reinforced plastic or metal. Type is dependent on the desired texture, the number of reuses required and method of form construction, installation, removal. form ties and storage when proposed (Waddell and Dobrowolski, 1993).

- **Wood forms** are made of rough boards, smooth plywood or medium and high density plastic coated plywood. Rough boards are most economical but require initial treatment to eliminate the soft dusty surface on its first use. Plain plywood can be used up to 4 times with proper care while plastic coated plywood can be reused at least 20 times. Sandblasted plywood can be used in case of desired grainy concrete surface (Waddell and Dobrowolski, 1993).

- **Plastic forms** include economic one time use Styrofoam, rigid extruded plastic, elastomeric rubbery flexible plastic and costly flexible vinyl liner. Fiberglass reinforced forms are also available. It provides good details but having a high initial cost requires multiple reuses (Waddell and Dobrowolski, 1993).

- **Metal forms** are used for smooth repetitive surface but require thorough cleaning procedures to preserve a uniform appearance when reused. Treatment with 5 percent chromic trioxide solution prevents mortar sticking to galvanized steel forms (Waddell and Dobrowolski, 1993).

Formwork Alignment and Joints

Spacing of tie rods, bolts and tie holes joints should be considered during the architectural design phase as they affect the final look of architectural concrete as shown in Figure 2.31 (Waddell and Dobrowolski, 1993).

Wooden and plastic cones may be available for hiding different tie rods holes sizes, thus satisfying additional aesthetic requirements (Waddell and Dobrowolski, 1993).

Formwork jointing shall be constructed to stand pressures and to prevent water leakage which may result in surface blemishes that might contrast with surface concrete color and are difficult to remove (Waddell and Dobrowolski, 1993).

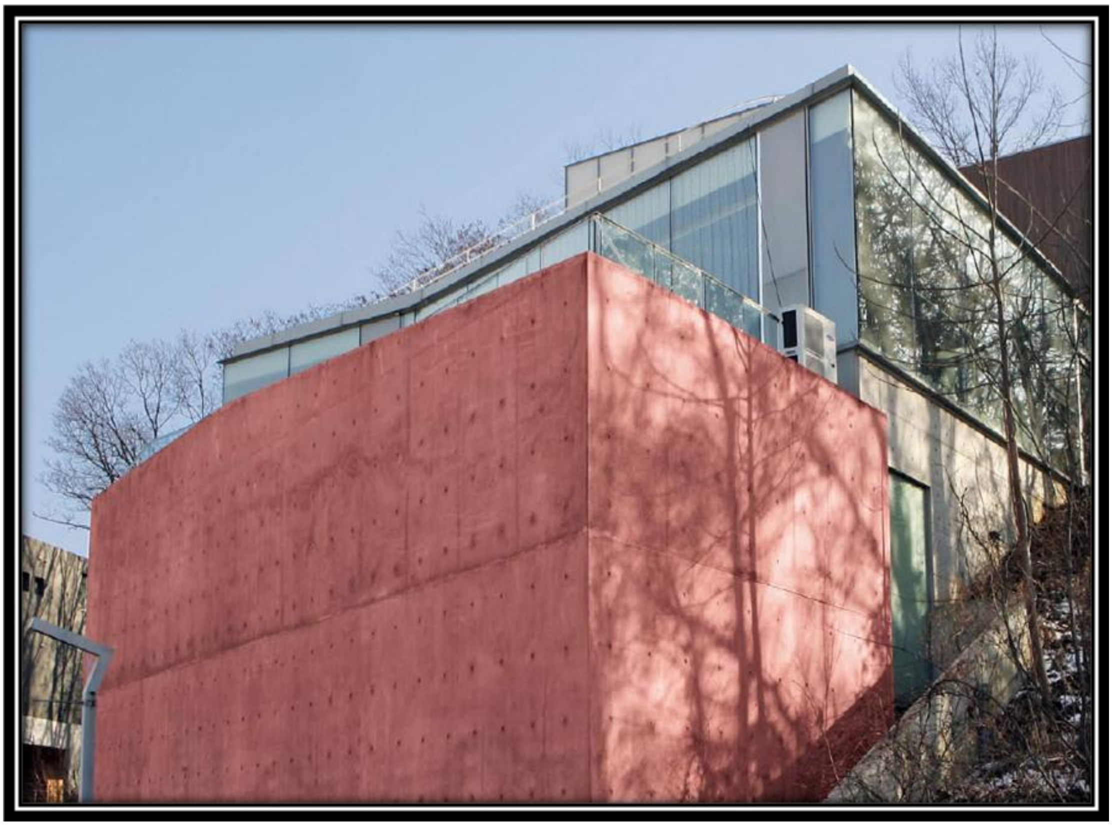

Figure 2.31 Spacing of tie rods, bolts and tie holes joints should be considered with architectural and pigmented concrete (Lanxess.com, 2013)

Formwork Release Agents

Release agent should have a field mockup sample to determine its compatibility with architectural concrete and any following application for surface finish (Waddell and Dobrowolski, 1993).

Application should produce very thin films preferably using a fan-type nozzle. It is always recommended to use manufacturer's instructions for film thickness (Waddell and Dobrowolski, 1993).

Each project should use one brand and batches should be ordered per project to have a consistent finish (ACI 303.1-98).

2.9.2 Mixing Considerations

Cast in place mixing

It is recommended to use the following batching method for producing pigmented concrete (www.bayferrox.us, 2013):

- Add carefully weighed mix aggregates (fine and coarse) to the mixer.
- Add one half or one third (depending on trial mix) of total batch water to the mixer.
- Add exact amount of pigment and begin mixing at full mixer speed for one minute minimum.
- Add cement in full, admixture and the remaining amount of water. Mix for a minimum of five minutes at full speed.
- Do not sprinkle dry concentrated pigments on the surface of fresh concrete.

Batching plant mixing

If an automated dispensing system for liquid pigments is unavailable it is recommended to consider the following (www.bayferrox.us, 2013):

- It is recommended to pour pigment directly from the bags if the mixing time is short or small aggregates are used, otherwise use disintegrating pigment bags in a similar sequence to cast-in place mixing technique.

- Keep all raw materials especially cement, coarse and fine aggregates as consistent as possible as any change may affect the final color for the entire project.

- Concrete loads should have uniform mix times. Delivery and placement should be quick as over mixing for longer than 90 minutes may affect color consistency.

- Air entrainment is necessary if freeze and thaw conditions are required, accordingly air content should range between 5 to 7 percent. Low air entrainment may result in spalling of the pigmented concrete surface while high air entrainment affects concrete strength and eliminates bleeding (Nasvik, 2004).

- Mixer should be cleaned thoroughly at the end of the job. Each new color should start with a clean drum.

- Avoid using calcium chloride or any admixture containing it with pigmented concrete to avoid efflorescence and discoloration.

- For a good color mix it is recommended not to overload the mixer as this reduces mixing efficiency. Mixer should be loaded no less than 40 percent of mixing load is required for the same reason.

Automated Liquid Dispensing System

Availability of an automated dispensing system for liquid pigmenting maximizes concrete color consistency, repeatability, ease of use and cost effectiveness. A typical system may include five polyethylene tanks of 4500 Kg bulk storage capacity as shown in Figure 2.32. Tanks hold primary color pigments and can be used like an inkjet printer to produce thousands of colors on demand. Colors are automatically pumped into a weigh vessel and then added to the truck mixer. Color recipes can be preprogrammed and used for a mix, match and preview process by architects, specifiers and clients to produce mockups even during the design phase. Last minute changes for color or even on-site load size can be achieved. Automated systems can also generate a batch printout log report for each load showing the precise mix and what truck delivered in case of problems on-site reducing compensation claims. They also provide a degree of repeatability for pigmented concrete projects that is similar to ordering paint made of blended color, using the same recipe would ensure the same color to be produced today, or in a month or a year. Stocking primary colors gets easier for inventory management than using powder pigments of various sized bags (Forgey, 2005).

Slump

Water Content should be adjusted depending on different pigment properties to produce a consistent slump of 125mm or less**.** Too much water tends to lighten the

Figure 2.32 Storage tanks of primary pigments that are pumped into liquid dispensing system using a computerized program (Forgey, 2005)

color of concrete and may produce a “washed- out” look. Water has an important effect on the final color of pigmented concrete. Adding water on site is prohibited as it may alter the pigment consistency in the mix in addition to long term shrinkage cracking. Ordering concrete with lower water content without using admixtures to increase workability may result in placing and finishing problems.

Placement and Compaction

Most equipment can be used for placement of pigmented concrete as long as it is clean from handling any other concrete types. Place concrete in uniform horizontal layers with no more depth than 90 cm for compaction. Architectural concrete requires extra care with compaction to eliminate air bugholes. Vibrators should be inserted at a spaced radius of action with a 50 percent overlap. Withdraw vibrators at a rate of 75 mm per second and keep vibrators 50 mm away from architectural face (ACI 303.1-98).

Curing

Curing technique used should not cause staining or discoloration of architectural concrete. It is advisable to use curing compounds recommended by pigment manufacturer. Wet burlap, burlap-backed plastic film or plastic film should not be used for curing horizontal architectural concrete (ACI 303.1-98). Many decorative concrete contractors eliminate curing as some decorating process may require open concrete surfaces. This may result in efflorescence, dusting and scaled surfaces (Nasvik, 2010). Curing can include wet curing for the first seven days. Wet curing covers might trap moisture containing calcium hydroxide at the surface resulting in efflorescence upon their removal. Covering concrete with a poly-plastic impermeable cover can be used but can result in uneven curing and color blemishes (Nasvik, 2010). Chemical membrane can be used also but when they lose bond small air voids develop on the concrete surface. As light is diffused and reflected in these voids later a hazy color appears that hides the pigmented concrete color underneath. Curing products are to be removed totally from concrete surface when an acid stain finish is required for pigmented concrete to allow for the stain to penetrate (Nasvik, 2010).

Sealing

Sealers are materials used to protect architectural concrete surface from weathering and contaminants from air. A sealer is expected to penetrate the concrete surface to a depth of 65 mm leaving little material at the surface (Waddell and Dobrowolski, 1993). Sealing is an important step for most pigmented and decorative concrete processes. Acrylic sealers allow water vapor to pass through slabs on ground, whereas curing compounds prevent hydration water from escaping concrete. When acrylic sealers are applied on curing compound formed membrane water vapor is still trapped in slab which results in blemishing formations at the surface. It is important to check compatibility of sealers and curing compounds as a loss of bond between them may occur. It is also important to note that sealers restrict moisture movement but should not be considered curing membrane (Nasvik, 2010).

Patching and Repair

Patching or repairs should not be permitted. With designer or architect permission only minor blemishes are allowed to be patched. Repairs can only be permitted if the resulting quality is equal to that of the approved mock-up and should start as soon as forms are removed (Bell, 1996). This shall permit patches to age together with the surrounding concrete thus reducing variation in color. All patch materials must have the same source as pigmented concrete. Because of the use of mortar with lower water-cement ratio for patches which would appear darker in color after drying, white cement should be added to the mortar patch mix. Mix proportions to be determined by trial and error. Aggregates might also be added for similar texture with patched concrete (Paris and Chusid, 1997). It is important to mask carefully the concrete around the patch by taping around the void, cutting zig-zag shapes of the crack edge and placing tape right on the hole edge (Nasvik, 2011).

2.10 Final Acceptance Considerations

An on-site mock-up should be approved and followed up throughout project duration (ACI 303.1-98).

Greater care should be given to the final finish, texture and pigmentation of the mock-up to match the required look per architectural element (ACI 303.1-98).

Patching and repairs will be accepted according to the blending capabilities and skill of the contractor involved (ACI 303.1-98).

Continuous inspections and acceptance procedures should be taken and records must be kept for every finished phase of the project (ACI 303.1-98).

2.11 Maintenance Considerations

Periodical maintenance is required for architectural concrete to prolong the aesthetic look and finish of its surface. Thus periodical sealing of exposed concrete surfaces is of extreme importance to minimize color fading, weathering and other pollutant effects (ACI 303.1-98).

CHAPTER 3

EXPERIMENTAL WORK

The experimental work was designed to meet the objectives of this investigation. The selection of materials used, the testing apparatus, procedures and mix proportions were carefully conducted to cope to a good extent with the actual field conditions in Egypt.

3.1 Materials

The materials used in this work were selected from commonly used constituents of concrete mixtures from local Egyptian sources except for the inorganic powder pigment, which is imported from Germany. These materials can be described as follows:

3.1.1 Grey Portland Cement

Grey ordinary Portland cement Type I was acquired from Helwan Cement Factory complying with ASTM C 159. The cement used was packed in 50 Kgs paper sacks. The cement had a typical Blaine fineness of 348 m^2/Kg and a density of 3.14 g/cm^3. Standard cement testing was performed before initiation of experimental work. The results of these tests are provided in Table 3.1.

3.1.2 White Portland Cement

White ordinary Portland cement Type I was acquired from Sinai Cement Factory complying with EN197/1-2000. The cement used was packed in 50 Kgs paper sacks.

The cement had a typical Blaine fineness of 382 m^2/Kg and a density of 2.95 g/$cm^{3.}$ Standard cement testing was performed before initiation of experimental work. The results of these tests are provided in Table 3.2.

Table 3.1 Typical Results of Standard Testing of Grey Cement Used

Test	Test Standard Specification	Tested Property	Result
Cement Fineness (Blaine)	ASTM C 204	Fineness	348 m^2/Kg
Specific Gravity	ASTM C 188	Density	3.14
Setting Time	ASTM C 191	Initial Setting	1hr 57min
		Final Setting	4hr 30min
Compressive Strength of Cement Mortar	ASTM C 109	3-days	22.66 Mpa
		7-days	30.10 Mpa

Table 3.2 Typical Results of Standard Testing of White Cement Used

Test	Test Standard Specification	Tested Property	Result
Cement Fineness (Blaine)	ASTM C 204	Fineness	382 m^2/Kg
Specific Gravity	ASTM C 188	Density	2.95
Setting Time	ASTM C 191	Initial Setting	1hr 45min
		Final Setting	3hr 55min
Compressive Strength of Cement Mortar	ASTM C 109	3-days	24.62 Mpa
		7-days	29.32 Mpa

3.1.3 Fine Aggregates

The siliceous sand used for all concrete mixtures was acquired from Katameya quarries. The sand had a fineness modulus of 2.6, a saturated surface-dry (S.S.D) specific gravity of 2.63 and a percent of absorption of 1.58 %, as shown in Table 3.3. According to ASTM C 136 sieve analysis was conducted and the results are illustrated in Table 3.4.

Table 3.3 Typical Results of Standard Testing of the Fine Aggregate Used

Test	Test Standard Specification	Tested Property	Result
Materials finer than 75µm (sieve No.200) in mineral aggregates by washing	ASTM C 117	Percent of materials finer than 75 µm	2.50%
Specific gravity and absorption of fine aggregates	ASTM C 128	Bulk Sp. Gravity	2.61
		Bulk Sp. Gravity at SSD Condition	2.63
		Apparent Sp. Gravity	2.66
		% Absorption	1.6

Table 3.4 Gradation for the Fine Aggregate Used

Sieve Size (mm)	Weight of Aggregate Retained (g)	Cumulative Weight (g)	Retained Cumulative (%)	Passing Cumulative (%)
4.75	0.4	0.4	0.08	99.92
2.36	7.0	7.4	1.48	98.52
0.6	41.5	48.9	9.78	90.22
0.3	264.8	313.7	62.74	37.26
0.09	157.9	471.6	94.32	5.68
0.075	25.4	497.0	99.40	0.60
Pan	3.0	500.0	100.0	0.0

3.1.4 Coarse Aggregates

The crushed dolomite used for all concrete mixtures was acquired from Suez Attaqa quarries with maximum nominal size 19 mm. The dolomite had a saturated surface-dry specific gravity of 2.56 and a percent of absorption of 2.4 %. Typical sieve analysis was conducted according to ASTM C 136. Sieve analysis results are presented in Table 3.5. Other tests were also conducted to determine the dolomite properties and results are presented in Table 3.6.

3.1.5 Water

Water used for both mixing and curing concrete for all mixtures was municipal Cairo water, which is expected to be free of alkalis, acids, excessive salts and other materials that may damage concrete.

Table 3.5 Gradation for the Coarse Aggregate Used

Sieve Size (mm)	Weight of Aggregate Retained (g)	Cumulative Weight (g)	Retained Cumulative (%)	Passing Cumulative (%)
25	0.0	0.0	0.00	100.00
19	21.2	21.2	0.71	99.29
12.5	862.0	883.2	29.44	70.56
9.5	619.8	1503.0	50.10	49.90
4.75	1316.4	2819.4	93.98	6.02
2.36	177.8	2997.2	99.91	0.09
Pan	2.8	3000.0	100.0	0.0

Table 3.6 Typical Results of Standard Testing of the Coarse Aggregate Used

Test	Test Standard Specification	Tested Property	Result
Materials finer than 75µm (sieve No.200) in mineral aggregates by washing	ASTM C 117	Percent of materials finer than 75 µm	0.98%
Specific gravity and absorption of fine aggregates	ASTM C 127	Bulk Sp. Gravity	2.50
		Bulk Sp. Gravity at SSD Condition	2.56
		Apparent Sp. Gravity	2.65
		% Absorption	2.28
Resistance to abrasion using the Los Angeles Machine	ASTM C 131	% Loss	50.17
Clay Lumps and Friable particles in Aggregate	ASTM C 142	Average % Loss	0.38%

3.1.6 Pigments

Inorganic color powder pigments were acquired from Lanxess Germany complying with ASTM C 979. Red and green pigments used were packed in 25 Kgs paper sacks while yellow pigment was packed in 20 Kgs paper sacks. Properties of pigments were provided by manufacturer (Lanxess.com, 2013) and presented in Table 3.7.

Table 3.7 Typical Properties of Powder Color Pigments Used

Test	Test Standard Specification	Results for Red Pigment (Bayferrox Red 110)	Results for Yellow Pigment (Bayferrox Yellow 910)	Results for Green Pigment (Green 2020)
Chemical Class		Synthetic iron oxide Fe_2O_3	Synthetic iron oxide Fe_2O_3	Synthetic chromium oxide Cr_2O_3
Content Fe_2O_3 %	DIN 55 913	96	85	-
Content Si_2O_2 + Al_2O_3 %	DIN 55 913	4.00	0.20	0.10
Content Cr_2O_3 %	X-ray flourescence	-	-	98.5-99.5
Water-soluble content %	DIN EN ISO 787	0.50	0.50	0.30
Sieve residue (0.045 mm sieve) %	DIN 53195	0.06	0.04	0.02
Loss on ignition at 1000 0C, 0.5 h %	DIN 55913	0.70	14.00	-
Loss on ignition at 1000 0C, 0.25 h %	DIN ISO 4621	-	-	0.40
Particle Shape	Electron Micrographs	Spherical	Acicular	Spherical
Predominant particle Size (µm)		0.09	0.1 * 0.6	0.30
Density (g/ml)	DIN EN ISO 787	5.0	4.1	5.2

3.2 Apparatus and Procedure

3.2.1 Aggregates Testing

In accordance with the corresponding ASTM standards specifications the testing of aggregates was conducted as follows:

- Sieve analysis of fine and coarse aggregates in accordance with ASTM C 136.
- Materials finer than 75 µm (No. 200 sieve) in mineral aggregates by washing in accordance with ASTM C 117.
- Clay lumps and friable particles in accordance with ASTM C 142.
- Specific gravity and absorption of fine and coarse aggregate in accordance with ASTM C 128 and C 127 respectively.
- Resistance to abrasion of small size coarse aggregates by use of Los Angeles machine in accordance with ASTM C 131.

3.2.2 Cement Testing

In accordance with the corresponding ASTM standards specifications the grey and white Portland cement testing was conducted as follows:

- Fineness of Portland cement by Air Permeability Apparatus in accordance with ASTM C 204.
- Density of hydraulic cement by Vicat Needle in accordance with ASTM C 191.
- Compressive strength of hydraulic cement mortar in accordance with ASTM C 109.

3.2.3 Concrete Mixtures

In this study, eighteen mixtures categorized into six groups were prepared according to the following parameters:

- Type of cement
- Pigment color
- Pigment content by weight of cement

The basic concrete mixture was one that is typical of moderate strength concrete. This mix has the following proportions:

Cement: 400 kg/m^3

Water: 200 kg/m^3

Fine Aggregates: 1062 kg/m^3

Coarse Aggregates: 671 kg/m^3

Table 3.8 summarizes the groups of mixtures regarding the type of cement, pigment color and content. The cement content was kept constant at throughout the study for all nineteen mixtures. The water to cement ratio was kept constant at 0.5 and no admixtures were used to minimize the parameters affecting the pigmented concrete color. Concrete mixing was conducted in an open pan mixer. First by mixing the pre-calculated quantities of coarse and fine aggregates, then adding two-thirds of total batch water and the exact amount of pigment and mixing for one minute. Finally adding the calculated amount of cement and the remaining amount of water. Concrete was further mixed for three minutes before performing of fresh concrete testing and the specimen preparation process. Figure 3.1 summarizes the experimental program followed in this study.

3.2.4 Fresh Concrete Testing

Workability

To test the workability of each mixture, slump of Portland cement concrete was performed on the fresh concrete produced, in accordance with ASTM C 143.

Air Content

To assess the air content of each concrete mixture, the test was performed on the fresh concrete produced, in accordance with ASTM C 231.

Unit Weight

To determine the fresh density of each concrete mixture, unit weight of Portland cement concrete the test was performed on the fresh concrete produced, in accordance with ASTM C 138. The value of unit weight is obtained by getting the ratio of the tamped weight of concrete in a container to the volume of that container.

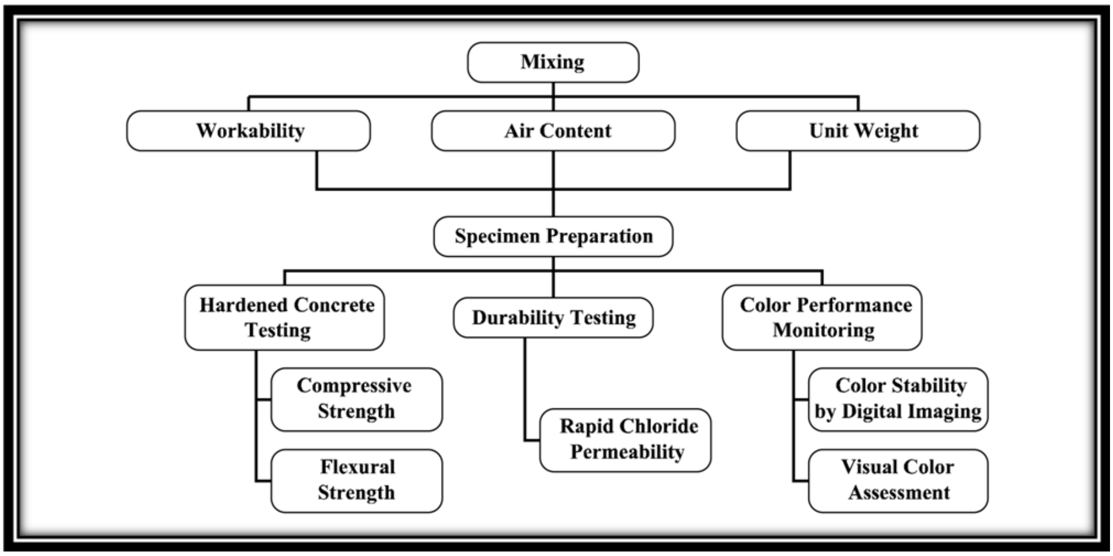

Figure 3.1 Experimental Program Testing Chart

3.2.5 Specimen Preparation

In this study nine standard cubes (150x150x150 mm) were prepared for each mixture complying with BS 1881 (part 116) and Egyptian standards. Two standard flexural strength beams (150x150x75 mm) were prepared for each mixture according to ASTM C 78. Three standard specimens of 100 mm diameter and 50 mm thickness were prepared for each mixture for rapid chloride permeability test complying with ASTM C 1202. Two standard slabs (300x300x75 mm) were prepared for each mixture and were used for visual inspection and digital color assessment of concrete pigmentation as shown in Figure 3.2.

Figure 3.2 Specimen Preparation for Hardened Concrete Testing

Table 3.8 Groups of Mixtures

Group	Mixture I.D.	Cement Type	Pigment Color	Pigment Percentage
0	Control	Grey	-	-
1	RG3	Grey	Red	3%
	RG7	Grey	Red	7%
	RG10	Grey	Red	10%
2	RW3	White	Red	3%
	RW5	White	Red	5%
	RW7	White	Red	7%
3	YG3	Grey	Yellow	3%
	YG7	Grey	Yellow	7%
	YG10	Grey	Yellow	10%
4	YW3	White	Yellow	3%
	YW5	White	Yellow	5%
	YW7	White	Yellow	7%
5	GG3	Grey	Green	3%
	GG5	Grey	Green	5%
	GG7	Grey	Green	7%
6	GW3	White	Green	3%
	GW5	White	Green	5%
	GW7	White	Green	7%

3.2.6 Hardened Concrete Testing

The following tests were conducted on the hardened concrete specimens:

Compressive Strength

Compressive Strength testing was conducted as shown in Figure 3.3 using concrete specimen in accordance to BS 1881 (part 116) and Egyptian standards. It was conducted using an “ELE” brand machine of 2000 kN capacity for all cubes after 7, 28 and 56 days.

Flexural Strength

Flexural Strength of concrete using simple beam with center point loading was conducted in accordance to ASTM C 78. It was conducted on two plain concrete beams. The test was conducted using an “ELE” brand machine of 2000 kN capacity as shown in Figure 3.4 for all beams after 28 days.

Figure 3.3 Compressive Strength Testing

Figure 3.4 Flexural Strength Testing

Rapid Chloride Permeability Test

Two standard specimens of 100 mm diameter and 50 mm thickness were tested for each mix design with a total of 38 samples. The specimens were air vacuumed and preconditioned with moist curing before testing. The test was conducted in accordance to ASTM C 1202 after 56 days of pouring. The apparatus for this test consists of a cell unit connected to a control apparatus which is linked to a computer. Control Proove-it apparatus is shown in Figure 3.5 while the cell unit is shown in Figure 3.6. The whole experiment and the resulting data are monitored and controlled through a programmed software. Concrete specimens are placed inside each cell, which is divided into two sections. Each cell has two poles that were connected to negative and positive sockets of the control box, where the black color represents the negative terminal and the red color represents the positive terminal. The control box can accommodate up to 5 cells at a time. This whole setting is regulated and monitored through a computer program that sets the experiment for its duration. RCPT is based on monitoring the amount of electrical current passing through the concrete specimens during a 6-hour period. A potential difference of 60 V is maintained across the ends of the concrete specimen inside each cell. One half of each cell is filled with a 3 % sodium chloride solution while the other half is filled with 0.3 N sodium hydroxide solution. The total electric charges, recorded in coulombs, forced to pass through the concrete specimen is related to the resistance of the specimen to chloride ion penetration. As the quality of concrete improves the passing charges decrease indicating low permeability classification. Although test results indicate the resistance to the penetration of chloride ions, it does not measure the cumulative chloride built-up or actual chloride content in concrete specimens.

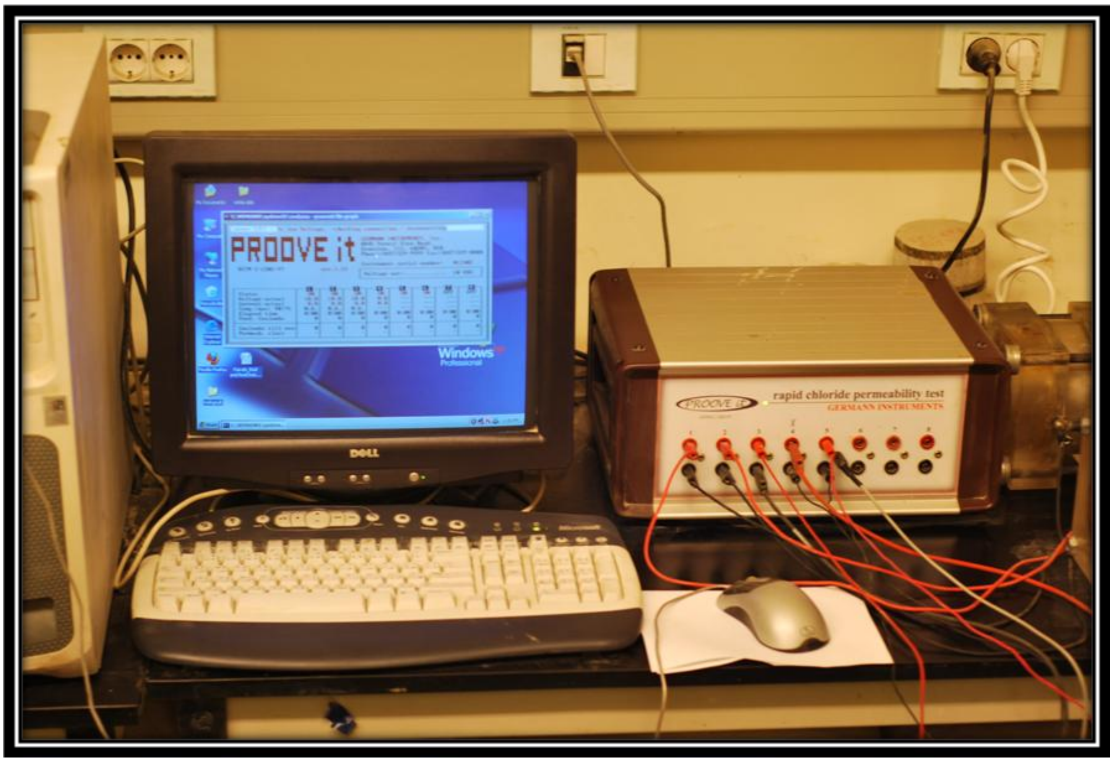

Figure 3.5 RCPT Proove-it Control Apparatus

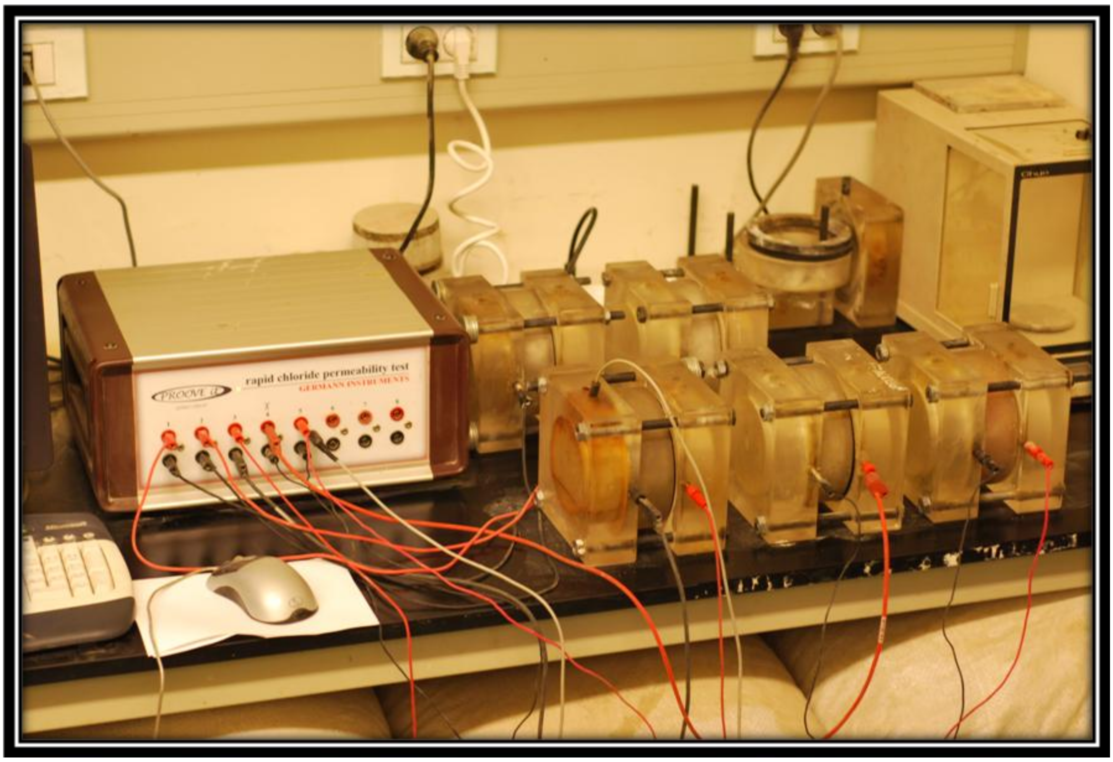

Figure 3.6 RCPT Cell Units

3.2.7 Pigment Color Performance Monitoring

Visual Color Assessment

Color comparisons were carried out after 56 days. Slab specimens 300 x 300 x 80 mm made with the same pigment were set together to permit visual comparisons one to another. The specimens were continuously stored in a standard moist room and after they were allowed to dry were used as the standard color for visual assessment.

Color Performance Monitoring by Digital Imaging

The pigment color performance monitoring was carried out on hardened concrete specimens at 7, 28 and 56 days before conducting the compressive strength test. One side of three cubes measuring 150 x 150 mm and the top surface of a slab measuring 300 x 300 mm where digitally photographed to monitor pigment color performance for each mixture. Cube surfaces that were finished with a trowel were somewhat different than surfaces formed against the wooden molds. This was taken in consideration by acquiring digital images for different surfaces for color assessment. The main purpose of this test is to assess distribution and masking effect of color pigments using different pigment dosages with both grey and white Type I Portland cement. It is difficult to compare digital images for concrete surfaces taken under different conditions of illumination. A standard setup for digital imaging was devised to capture the true color of concrete samples under investigation in a dark room using an interchangeable lens Nikon D-40 digital SLR camera was set at a constant level of 0.95 m fixed to an aluminum tripod, specimen was set at constant level of 0.80 m and distance between camera lens and specimen was set at 1.25 m. This setting was used to photo shoot all specimens as shown in Figure 3.7.

Camera Settings were as follows:

- Mode: Programmed mode "P"
- Metering: Center weighed
- Effects: Vivid
- White balance: Automatic
- ISO sensitivity value: 100
- Images output file: 2 output files for each image; RAW (with a file extension *.NEF produced by Nikon) and JPEG (normal size).

A Nikon Speedlight SB-800 flash was attached to the camera to provide a standardized lighting and the settings were as follows:

- Mode: Auto flash mode "TTL", were camera automatically controls the flash based on exposure control information.
- Exposure: Balanced Fill-Flash "BL", were flash output level provides automatically balanced exposure for the main subject and the background.
- ISO sensitivity value: 100
- Extra Diffuser: Off
- Flash tilt angle: 90 Degrees.

A Nikkor prime lens with a fixed focal length of 50 mm was chosen for photographing samples with manual focus. Prime lenses offer very sharp images, with better quality especially when shooting under demanding light conditions.

All images were captured with lens settings as follows:

- Focal length: 50 mm
- F/stop: 1/60 s
- Lens Focus Control: Manual

The scheme aimed at ensuring that the digital images acquired for all samples were shot with the same settings to obtain color consistency for later comparisons. Surface images were later uploaded to iMac desktop computer and were subsequently corrected then analyzed by the software “Adobe Photoshop Creative Suite 5” package. As explained earlier in this study, camera RAW correction procedure aims at rounding-up or distilling billion colors produced per image down to the best 16 million and this process is called "camera RAW correction". The main screen for the software's correction procedure is shown in Figure 3.8. Further fine tuning for captured images was performed during correction using the "Basic" side window with the following settings:

- White Balance: Custom
- Temperature: 5000
- Tint: +1
- Exposure, Recovery, Fill Lights, Blacks, Brightness, Contrast, Clarity, Vibrance and Saturation were set using Default settings.
- Standard embedded profile for output images: IEC61966-2.1 sRGB 16 bit.

Figure 3.7 Standard Setup for Acquiring Digital Images for all Specimens

White balance temperature was changed from 4750 K as captured to 5000 K known as CIE reference illuminant D50 which is used to compute L*a*b* data in Adobe Photoshop. It is important to note that this technique is device dependant, for the

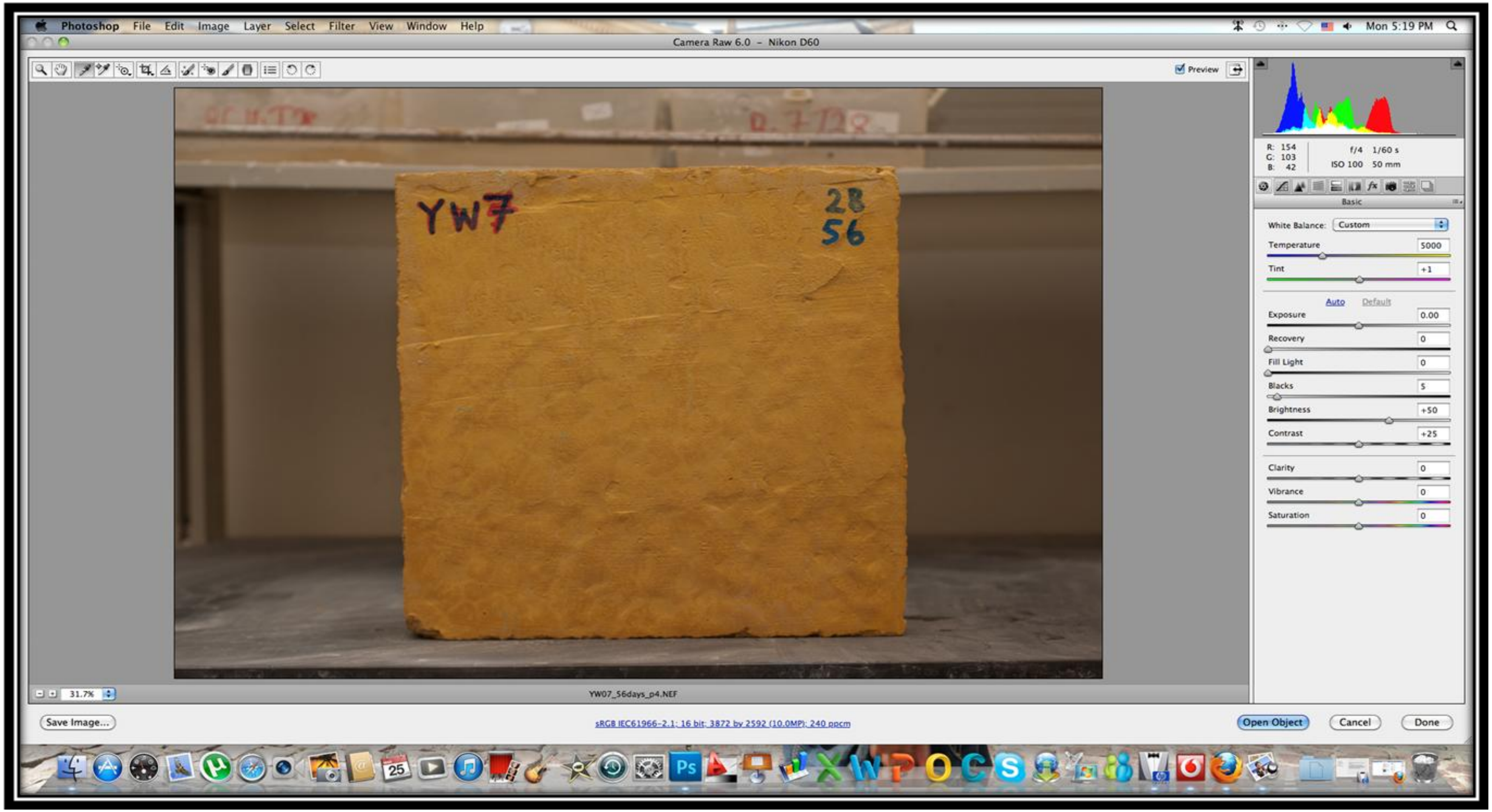

Figure 3.8 Adobe Photoshop CS5 main screen for RAW correction procedure

readings to be repeatable the process should be performed using the same platform, whether Windows or Macintosh and using the same version of Adobe Photoshop software (Pascale, 2003).

- Correction window allows using a “crop tool” to that is used to cut off image background and resulting in an image with only the concrete surface under investigation as shown in Figure 3.9.

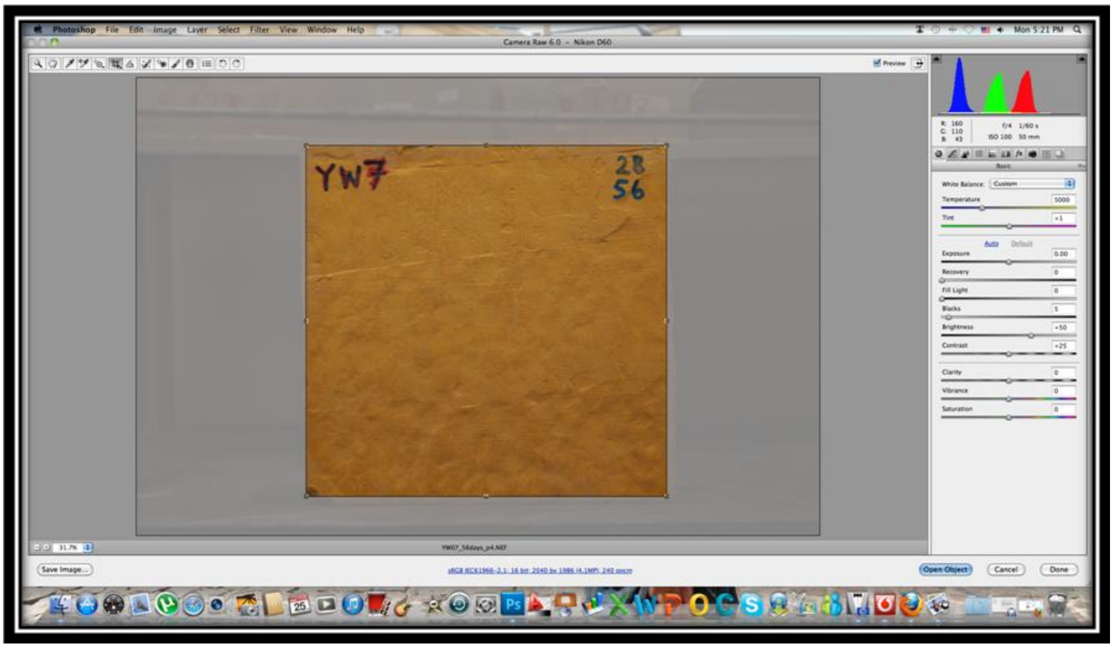

Figure 3.9 Cropping Concrete Surface for Color Measurement

- After correction procedures are set image files are opened in Adobe Photoshop Creative Suite 5 Software in RGB 16 bit color space.

- This will produce color information summing up to 250 thousand pixels for each 150x150 mm cube surface.

- Color space is modified from RGB 16 bit to L*a*b* 16 bit using “Image” in the upper menu, “Mode” in the sub menu and choosing Lab Color and 16 Bits/Channel option as shown in Figure 3.10.

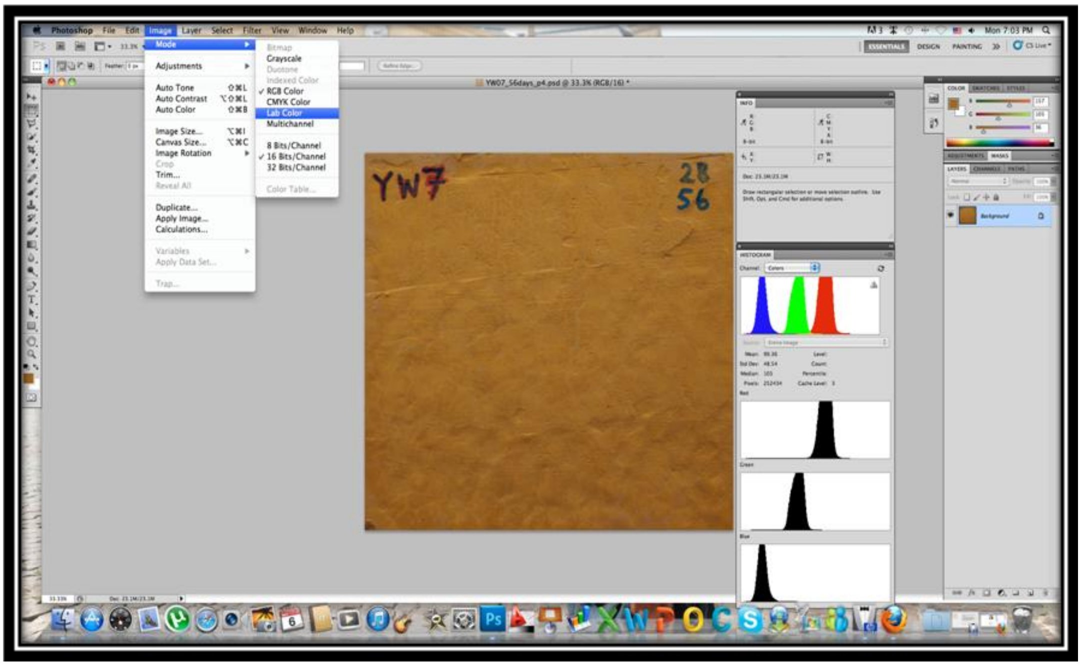

Figure 3.10 Modifying from RGB to L*a*b* space in Adobe Photoshop CS5

- Color readings are obtained using “Image” in the upper menu, “Adjustments” sub menu then by choosing the “Curves” option as shown in Figure 3.11.

- This option opens a window showing a composite histogram for all three channels L*, a* and b* with an option of separating each channel in separate histogram. Data values are obtained from each separate histogram for L*, a* and b* then manually entered in an Excel sheet for further calculations for all image files as shown in Figure 3.12. For each mixture, the average values of the chromatic parameters L*, a* and b* were calculated and evaluated at 7, 28 and 56 days.

- Another method can be applied by moving Adobe Photoshop “Eyesdropper tool" on the image. All image readings per pixel including L*a*b* will be shown on a side “Navigator” window as the tool is moved on the surface (image) in question.

- Image file can be saved after RAW correction and adjustments for future measurements and reference in Adobe Photoshop *.PSD file format or in the more widely used *.TIFF file format.

This is perhaps the first time such technique of computing L*a*b* color data from RAW digital images is developed and applied to concrete.

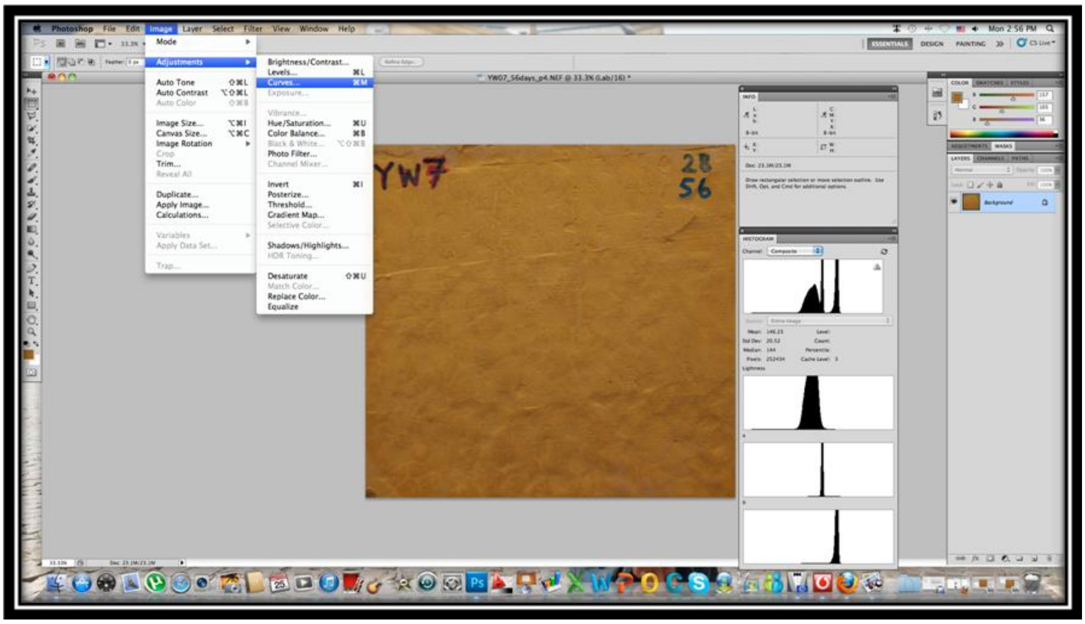

Figure 3.11 Adobe Photoshop CS5 main screen for RAW correction

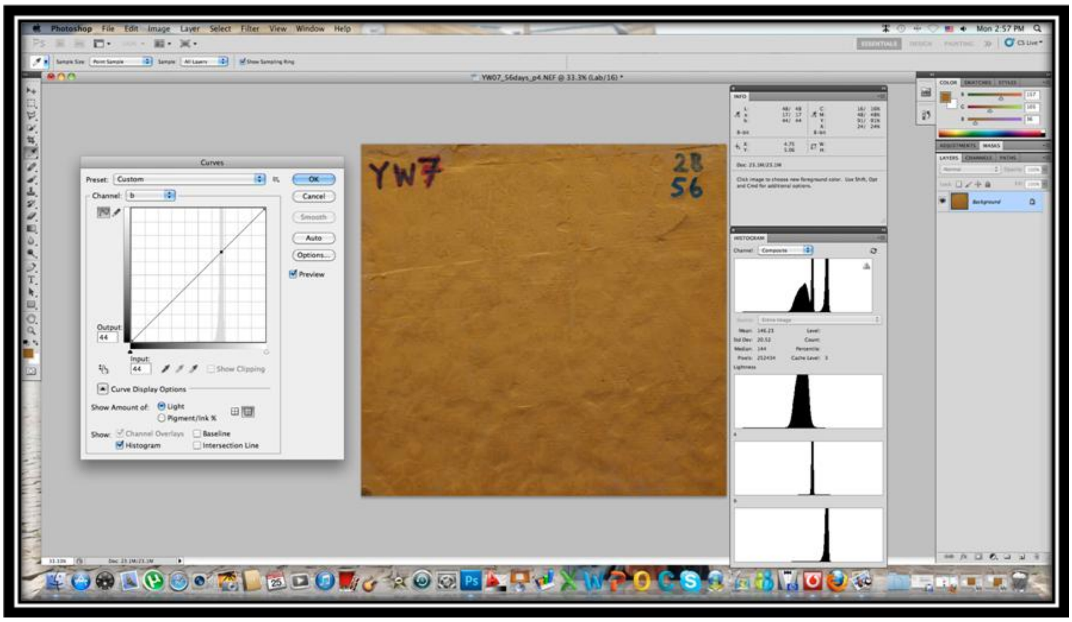

Figure 3.12 Using Adobe CS5 L*a*b* Histogram & measurement

CHAPTER 4

RESULTS AND ANALYSIS

In this chapter the results of the experimental work are presented and discussed. The results are divided into two sets where Set I mixtures were done with ordinary grey Portland cement while Set II mixtures were prepared with ordinary white Portland cement. Both sets were mixed with iron-oxide red pigment, iron-oxide yellow pigment and chromium oxide green pigment.

4.1 Fresh Concrete

Fresh concrete mixtures were evaluated for workability, air content and unit weight. Test was conducted according to relevant standards and the key results are listed in Table 4.1.

4.1.1 Workability

From Table 4.1 and Figure 4.1, it can be noticed that the different pigments color had varying influence on workability. Water-to-cement ratio ranged between 0.48 to 0.53 producing workable mixtures without the use of admixtures. Control grey cement mixture had a slump of 90 mm. Increasing dosage of red and yellow pigments caused gradual loss of slump with both grey cement mixtures ranging between a maximum of 80 mm and 55 mm for red and yellow pigment respectively at a dosage of 3 percent pigment by weight of cement and a minimum of 45 mm and 35 mm for red and yellow pigment respectively at a dosage of 10 percent pigment by weight of cement.

Table 4.1 Fresh Concrete Results

Mix ID	Cement Type	Pigment Content (kg)	w/c	Slump (mm)	Air Content	Unit Weight (kg/m^3)
Control	Ordinary Grey Cement	-	0.50	90	1.9%	2515
RG3	Ordinary Grey Cement	12	0.50	80	2.2%	2545
RG7	Ordinary Grey Cement	28	0.48	60	2.5%	2510
RG10	Ordinary Grey Cement	40	0.48	45	2.5%	2541
RW3	Ordinary White Cement	12	0.50	150	2.0%	2531
RW5	Ordinary White Cement	20	0.50	70	1.4%	2531
RW7	Ordinary White Cement	28	0.50	130	1.3%	2567
YG3	Ordinary Grey Cement	12	0.50	55	2.6%	2531
YG7	Ordinary Grey Cement	28	0.50	40	2.4%	2521
YG10	Ordinary Grey Cement	40	0.50	35	2.3%	2484
YW3	Ordinary White Cement	12	0.50	40	1.5%	2521
YW5	Ordinary White Cement	20	0.53	75	1.7%	2626
YW7	Ordinary White Cement	28	0.53	110	2.0%	2548
GG3	Ordinary Grey Cement	12	0.53	60	2.0%	2372
GG5	Ordinary Grey Cement	20	0.53	55	1.8%	2548
GG7	Ordinary Grey Cement	28	0.50	95	1.5%	2384
GW3	Ordinary White Cement	28	0.50	55	1.8%	2524
GW5	Ordinary White Cement	20	0.53	80	1.6%	2530
GW7	Ordinary White Cement	28	0.50	40	1.3%	2531

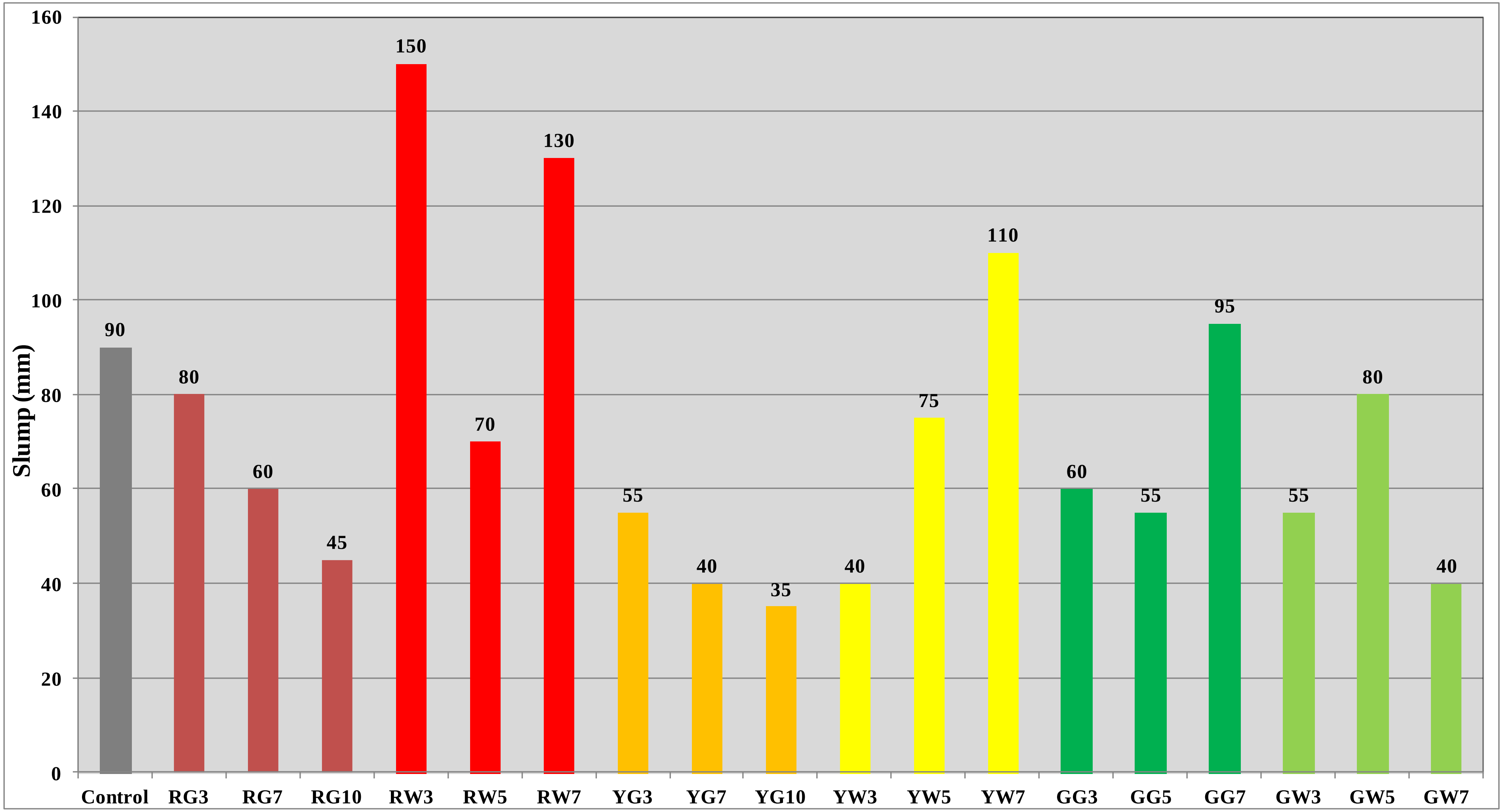

Figure 4.1 Slump Test Results

This is attributed to the needle shaped particles of the yellow pigment having a larger surface area than the spherical shaped particles of the red pigment causing the rapid decline in workability in compliance with Lee et al. 2004. Adding red pigment to white cement mixtures resulted in inconsistent results. Slump values ranged between a maximum of 150 mm at a dosage of 3 percent pigment to a minimum of 70 mm at a dosage of 5 percent pigment by weight of cement. Adding yellow pigment caused remarkable increase in slump values with white concrete mixtures. Slump values ranged between a maximum 110 mm at 7 percent yellow pigment and a minimum of 40 mm at 3 percent yellow pigment dosage by weight of cement. Adding green pigment had a varying effect on slump results. Gradual decrease in slump occurred with adding 3 to 5 percent of green pigment to mixtures reaching a minimum of 55 mm. Maximum slump results of 95 mm at a dosage of 7 percent pigment mixed with grey cement and 80 mm at a dosage of 5 percent pigment mixed with white cement. This might be attributed to the spherical shaped green pigments that are larger in size than red pigments and consists of chromium oxide as its main ingredient. Repulsive forces are created between the particles resulting in better workability at higher dosages of green pigments complying with Lee et al. (2004). Inconsistencies in slump could be attributed to the changes in the surface area of pigments.

4.1.2 Air Content

Air content results for the nineteen mixtures are shown in Figure 4.2. Chart shows fresh concrete results ranging from 1.3 to 2.6% for all mixtures regardless of the used pigments. The results for the two sets of mixtures had a close range since the grey ordinary cement and the white ordinary cement had ranges of 1.5-2.6%, 1.3-2.0%,

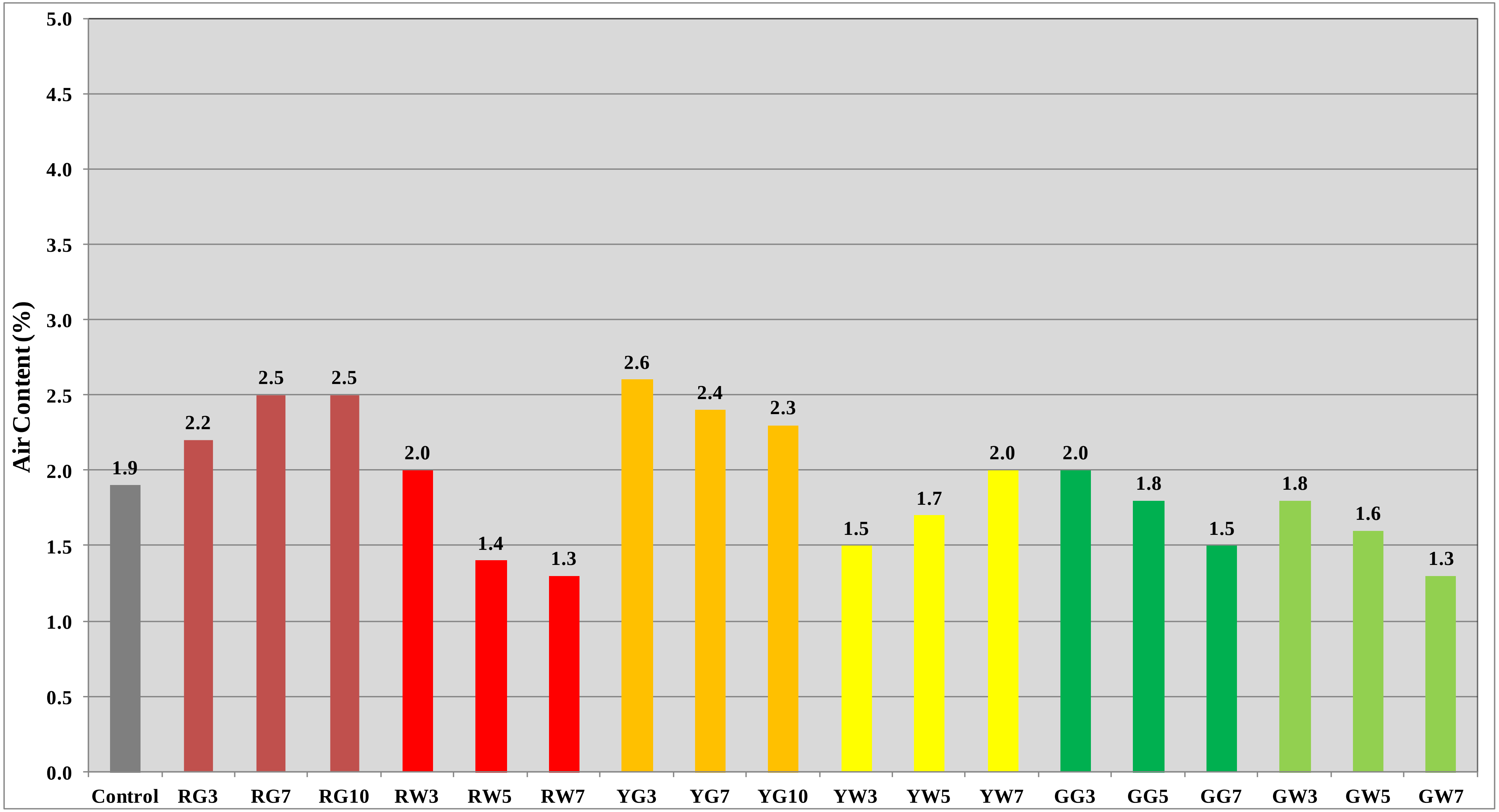

Figure 4.2 Air Content Results

respectively. It can also be observed that grey cement mixtures had generally higher air content than white cement mixtures for similar color pigments. Adding different color pigments resulted in inconsistent patterns of air content percentages. Most mixtures show a decrease in air content with increasing pigment dosage. Mixtures made with red pigment grey cement and yellow pigment white cement show an increase in air content as pigment dosage increases. It can be concluded that the type of pigment did not have a significant effect on air content results.

4.1.3 Unit Weight

The fresh concrete unit weight was determined for the nineteen mixtures as shown in Figure 4.3. The unit weight values had a narrow range of 2372 to 2626 kg/m^3 for all mixtures irrespective of constituents used. The results for the two sets of mixtures had a close range since the grey ordinary cement and the white ordinary cement had ranges of 2372 to 2548 kg/m^3, 2521 to 2626 kg/m^3 respectively. There was no definite trend between conjugate mixtures of the two groups. This implies that there are no major changes introduced by pigments affecting air content and unit weight. Further work needs to be done to evaluate the effect of different pigments and dosages on air content and unit weight values.

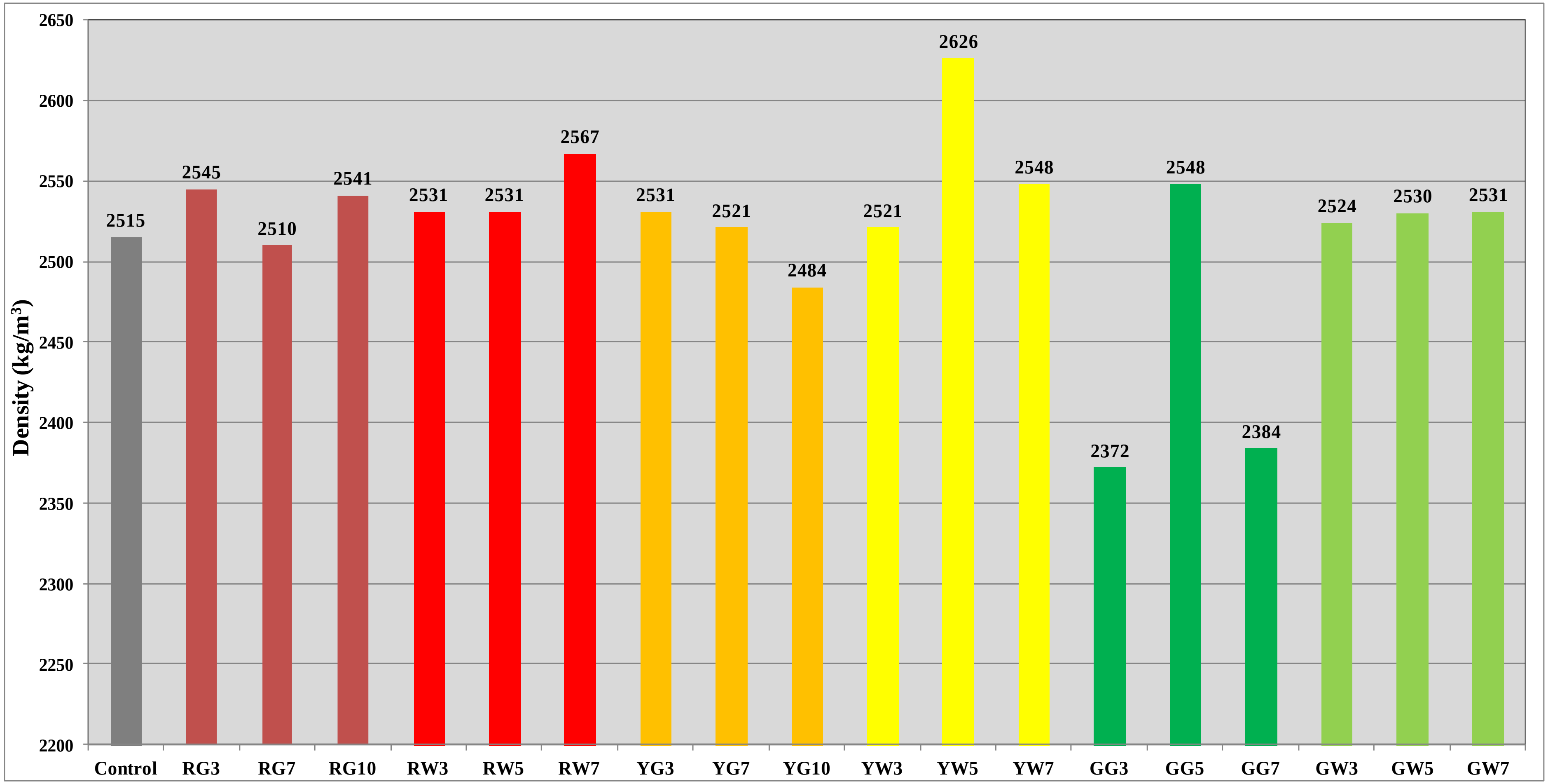

Figure 4.3 Unit Weight Test Results

4.2 Hardened Concrete

In this section, hardened concrete properties are evaluated. Assessed parameters are compressive strength, flexural strength, rapid chloride permeability, ponding and pigment color performance monitoring.

4.2.1 Compressive Strength

Results of compressive strength tests performed at 7, 28 and 56 days are listed in Table 4.2, and illustrated in Figures 4.4, 4.5 and 4.6 for the tested mixtures. For 7-day strength, results ranged between 10.9 to 34.7 MPa, for 28-day strength, results ranged between 16.6 to 41.7 MPa, while they ranged from 20.1 to 42.3 MPa for 56-day strength.

From Figure 4.4, it can be observed that the type of cement influenced the compressive strength results. The 7-day strength results ranged between 16.2-34.7 MPa and 10.9-20.1 MPa for pigmented grey mixtures and pigmented white mixtures respectively. This might be attributed to the low content of C_4AF in white cement resulting in a lower 7-day compressive strength.

From Figure 4.5, the 28-day strength results ranged between 22.2-41.6 MPa and 16.6-23.4 MPa for pigmented grey mixtures and pigmented white mixtures respectively. This suggests that pigmented white cement mixtures exhibit higher gain in strength values after 28 days.

From Figure 4.6, the 56-day strength results ranged between 30.1-48.3 MPa and 20.0-31.6 MPa for pigmented grey mixtures and pigmented white mixtures respectively.

Table 4.2 Compressive Strength Results

Mix ID	Cement Type	Pigment Content (kg)	w/c	Compressive Strength (MPa)		
				7 days	28 days	56 days
Control	Ordinary Grey Cement	-	0.50	30.4	33.5	36.4
RG3	Ordinary Grey Cement	12	0.50	25.8	34.5	35.9
RG7	Ordinary Grey Cement	28	0.48	24.1	29.4	33.5
RG10	Ordinary Grey Cement	40	0.48	34.7	41.7	42.3
RW3	Ordinary White Cement	12	0.50	10.9	20.3	25.0
RW5	Ordinary White Cement	20	0.50	13.9	22.6	29.2
RW7	Ordinary White Cement	28	0.50	18.4	20.9	26.2
YG3	Ordinary Grey Cement	12	0.50	16.3	23.5	31.7
YG7	Ordinary Grey Cement	28	0.50	23.0	28.3	32.9
YG10	Ordinary Grey Cement	40	0.50	25.0	29.7	35.1
YW3	Ordinary White Cement	12	0.50	20.2	20.6	31.6
YW5	Ordinary White Cement	20	0.53	19.0	21.9	29.2
YW7	Ordinary White Cement	28	0.53	13.0	16.6	20.1
GG3	Ordinary Grey Cement	12	0.53	26.6	29.3	32.5
GG5	Ordinary Grey Cement	20	0.53	21.2	30.8	37.8
GG7	Ordinary Grey Cement	28	0.50	24.6	26.9	32.3
GW3	Ordinary White Cement	28	0.50	12.1	21.5	26.1
GW5	Ordinary White Cement	20	0.53	14.7	20.3	24.2
GW7	Ordinary White Cement	28	0.50	16.4	23.3	27.8

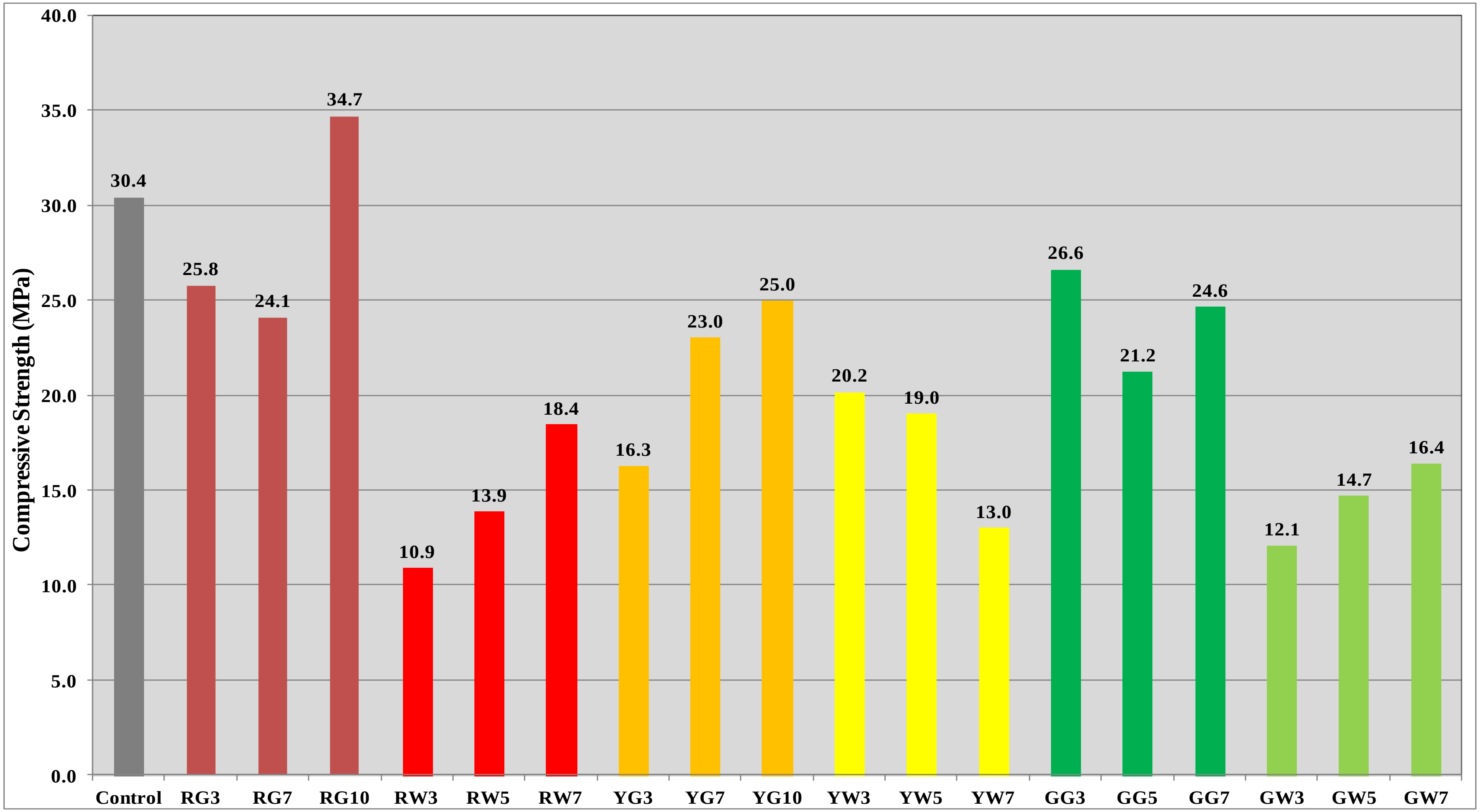

Figure 4.4 7-Day Compressive Strength Results

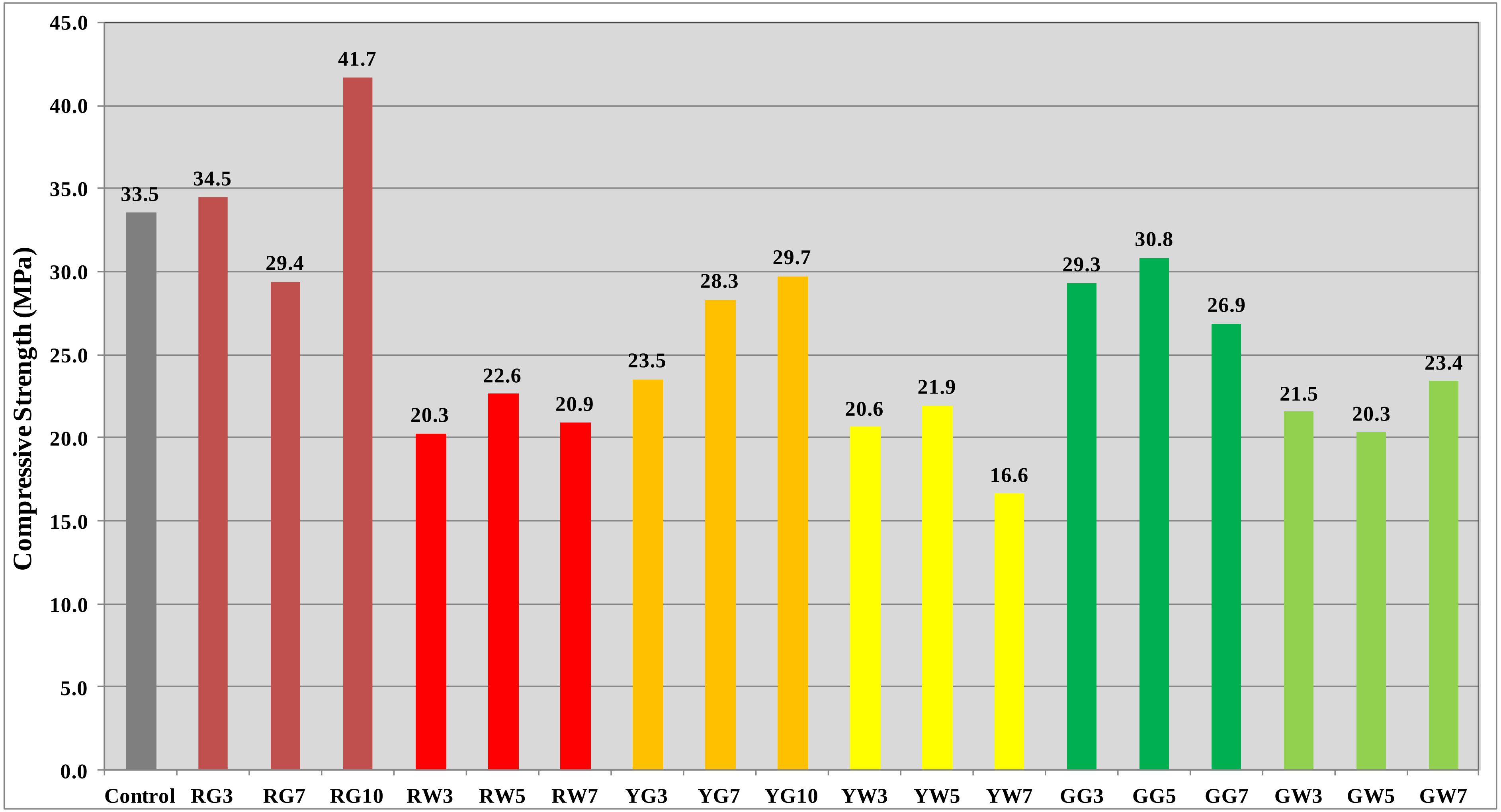

Figure 4.5 28-Day Compressive Strength Results

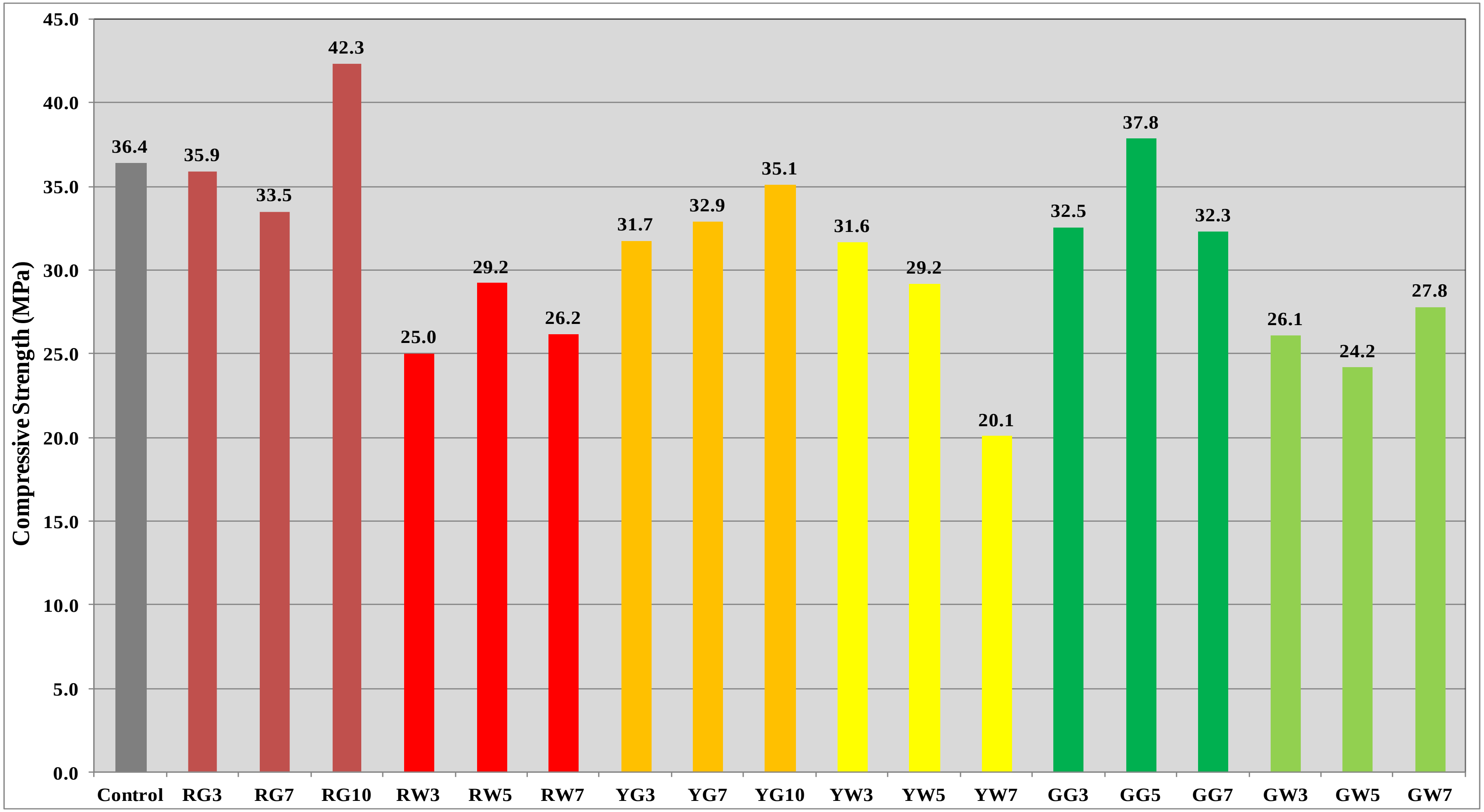

Figure 4.6 56-Day Compressive Strength Results

Increasing dosage of red pigment at 3 percent and 7 percent resulted in a closer range of compressive strength values varying between a minimum of 24.1 to 25.8 MPa, 29.4 to 34.5 Mpa and 33.5 to 35.9 MPa at 7, 28 and 56 days respectively. While gradual increase of yellow pigment dosage to grey concrete mixtures from 3 percent to 10 percent by weight of cement resulted in an increase in compressive strength values of 16.3 to 25 MPa, 23.5 to 29.7 Mpa and 31.7 to 35.1 MPa at 7, 28 and 56 days respectively. Grey concrete mixtures with a maximum dosage of 10 percent red and yellow pigments resulted in higher compressive strength values of 25 to 34.7 MPa, 29.7 to 41.7 MPa and 35.1 to 42.3 MPa at 7, 28 and 56 days respectively. Different dosages of green pigment mixed with grey concrete mixtures ranging between 3 percent to 7 percent by weight of cement resulted in a closer range of compressive strength values of 21.2 to 26.6 MPa, 26.9 to 30.8 MPa and 32.3 to 37.8 MPa at 7, 28 and 56 days respectively. Results suggest that green pigment dosage of 5 percent produced higher compressive strength results of 30.8 MPa and 37.8 MPa at 28 and 56 days respectively.

Standard Specification for Pigments for Integrally Colored Concrete implies that using the prescribed pigment dosage shall have a 28-day compressive strength of no less than 90% than that of the control mix (ASTM C979/C979M, 2011). The ratio between 28-day compressive strength results of pigmented and unpigmented concrete mixtures is illustrated in Figure 4.7. Pigmented grey cement mixtures had a 28-day compressive strength ratio of 88 to 124 percent, 70 to 89 percent and 80 to 92 percent for red, yellow and green pigments respectively compared with control grey cement mixture. Pigmented white cement mixtures had a 28-day compressive strength ratio of

79 to 89 percent, 65 to 86 percent and 80 to 92 percent for red, yellow and green 79 pigments respectively compared with control white cement mixture.

The ratio between 56-day compressive strength results of pigmented and unpigmented concrete mixtures is illustrated in Figure 4.8. Pigmented grey cement mixtures had a 56-day compressive strength ratio of 92 to 116 percent, 87 to 96 percent and 89 to 104 percent for red, yellow and green pigments respectively compared with control grey cement mixture. This shows that properties of pigments added to concrete mixtures are in compliance with ASTM specifications with respect to compressive strength results The ratio between 28-day compressive strength results of pigmented and unpigmented concrete mixtures is illustrated in Figure 4.7. Pigmented grey cement mixtures had a 28-day compressive strength ratio of 88 to 124 percent, 70 to 89 percent and 80 to 92 percent for red, yellow and green pigments respectively compared with control grey cement mixture. Pigmented white cement mixtures had a 28-day compressive strength ratio of 79 to 89 percent, 65 to 86 percent and 80 to 92 percent for red, yellow and green pigments respectively compared with control white cement mixture. Pigmented white cement mixtures had a 56-day compressive strength ratio of 81 to 85 percent, 65 to 103 percent and 79 to 90 percent for red, yellow and green pigments respectively compared with control white cement mixture. Compressive strength results of white cement mixtures were more affected by addition of pigments than grey cement mixtures. Fluctuations in compressive strength results of pigmented white cement mixtures might be attributed to current inconsistencies in the manufacturing process of Egyptian white cement rendering it un-recommended for use with structural concrete mixtures. However, it should be noted that white cement has been documented to yield comparable results to that of grey cement when properly produced.

The strength gain ratio from 7 to 28 days is shown in Figure 4.9. The ratio varied between 69-92% and 54-98% for pigmented grey mixtures and pigmented white mixtures respectively. The strength gain ratio from 28 to 56 days is shown in Figure 4.10. The ratio varied between 81-99% and 65-90% for pigmented grey mixtures and pigmented white mixtures respectively.

Overall, the compressive strength results show inconsistencies which could be attributed to differences in chemical composition and surface area of pigments used. This could result in varying surface chemistry behavior. On the whole the drop in compressive strength for pigmented mixtures ranged between 10 to 20 percent for pigmented grey and white concrete mixtures respectively.

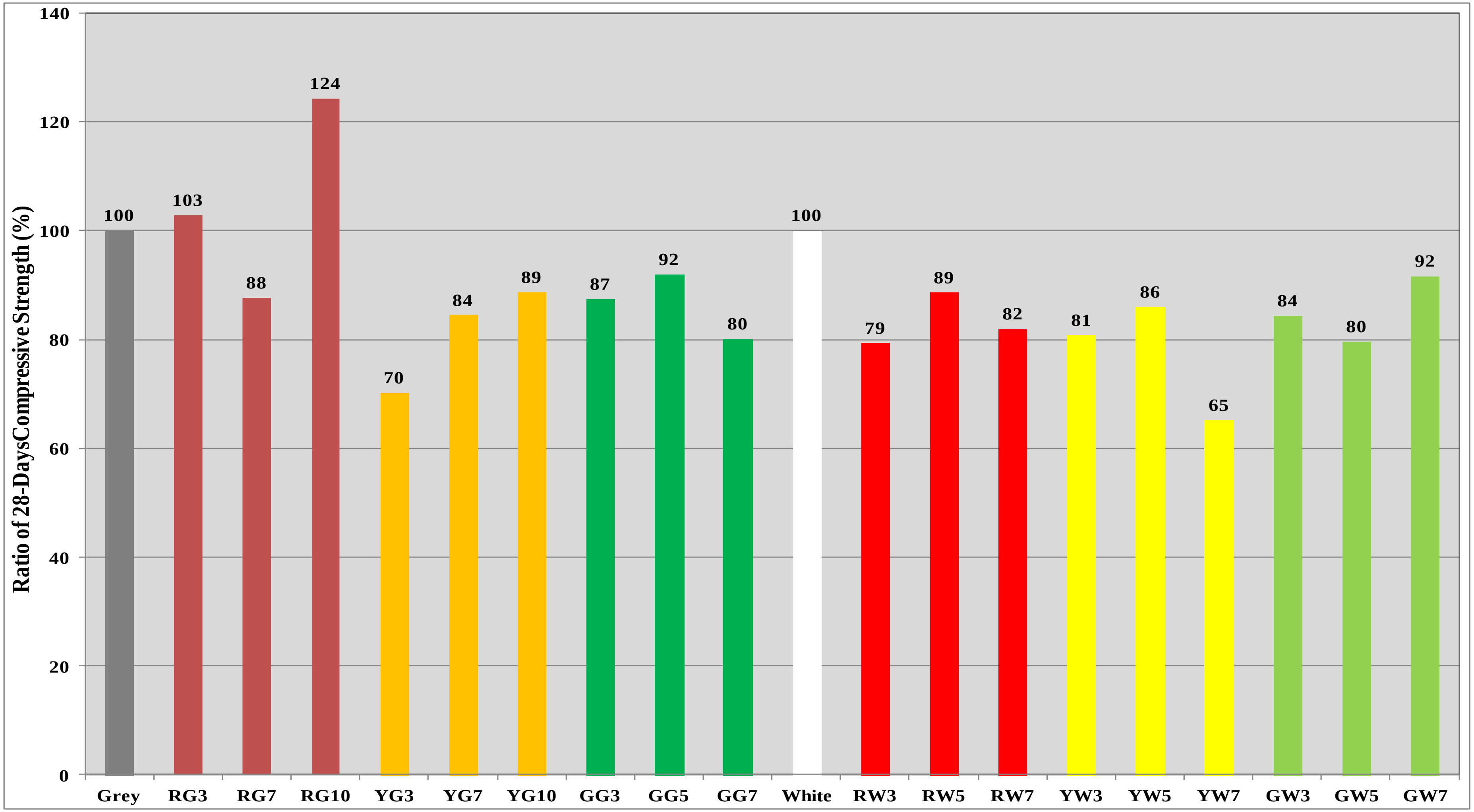

Figure 4.7 The Ratio between 28-Day Compressive Strength Results of Pigmented and Unpigmented Mixtures

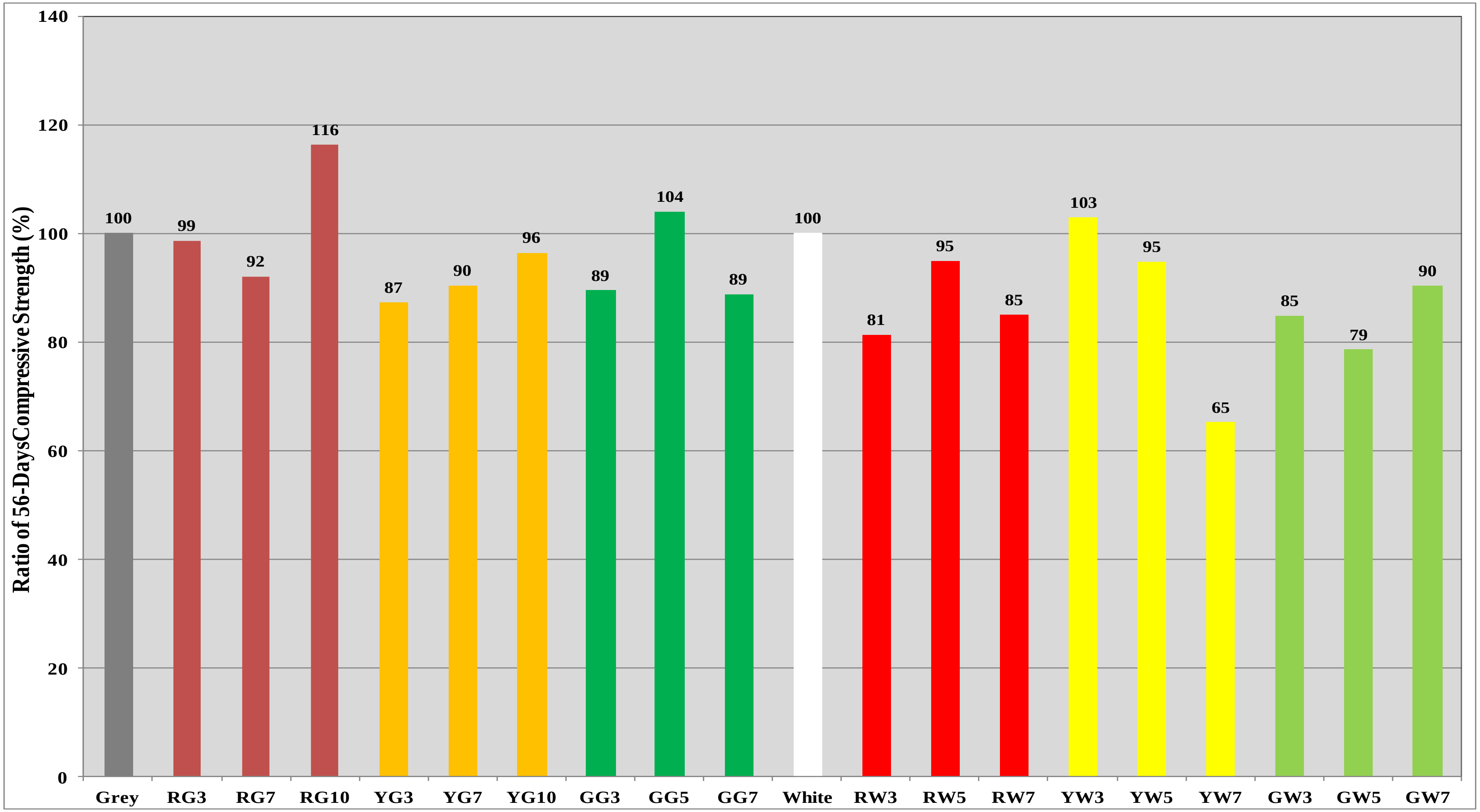

Figure 4.8 The Ratio between 56-Day Compressive Strength Results of Pigmented and Unpigmented Mixtures

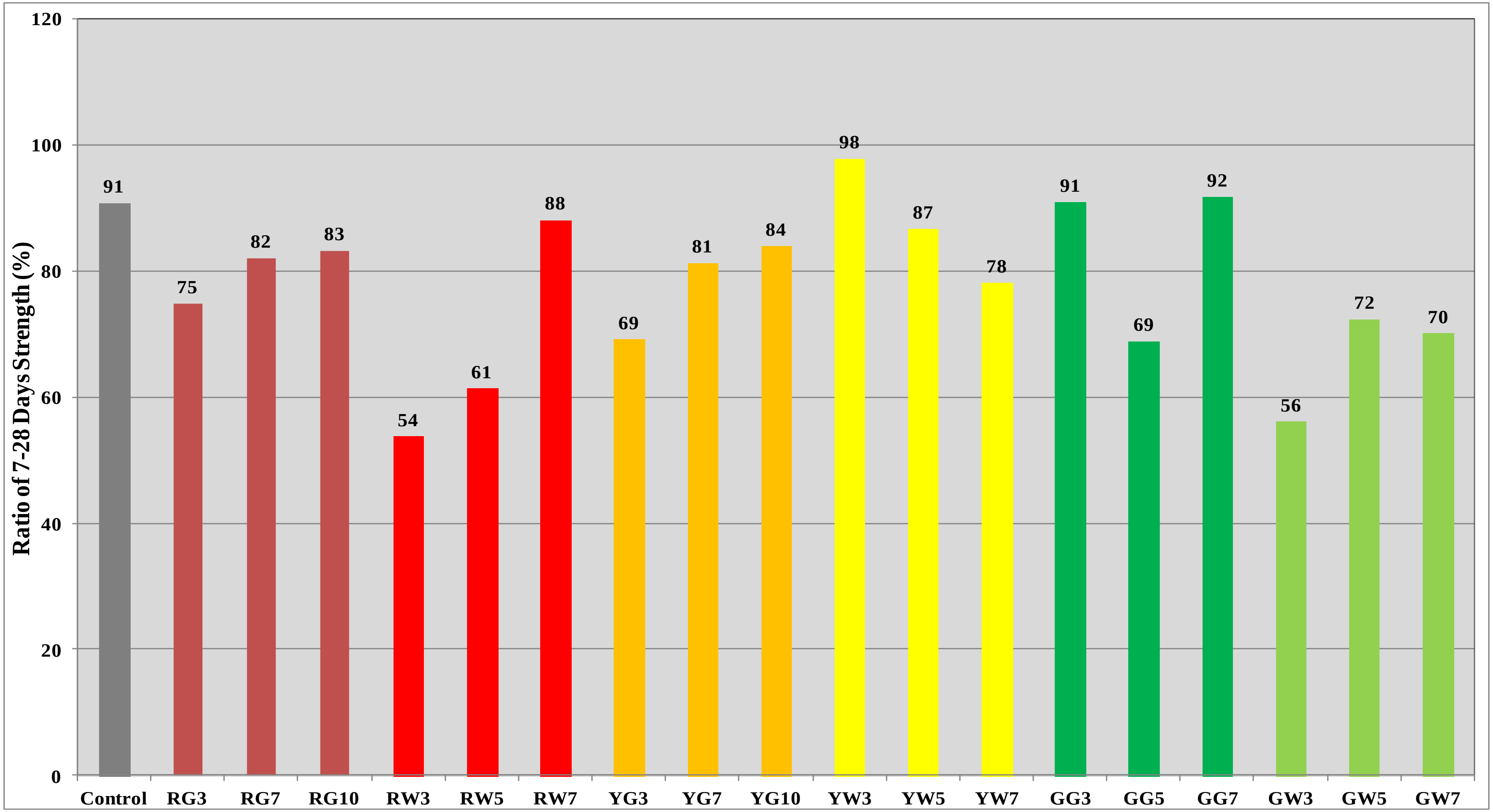

Figure 4.9 The Ratio between 7-Day and 28-Day Compressive Strength Results

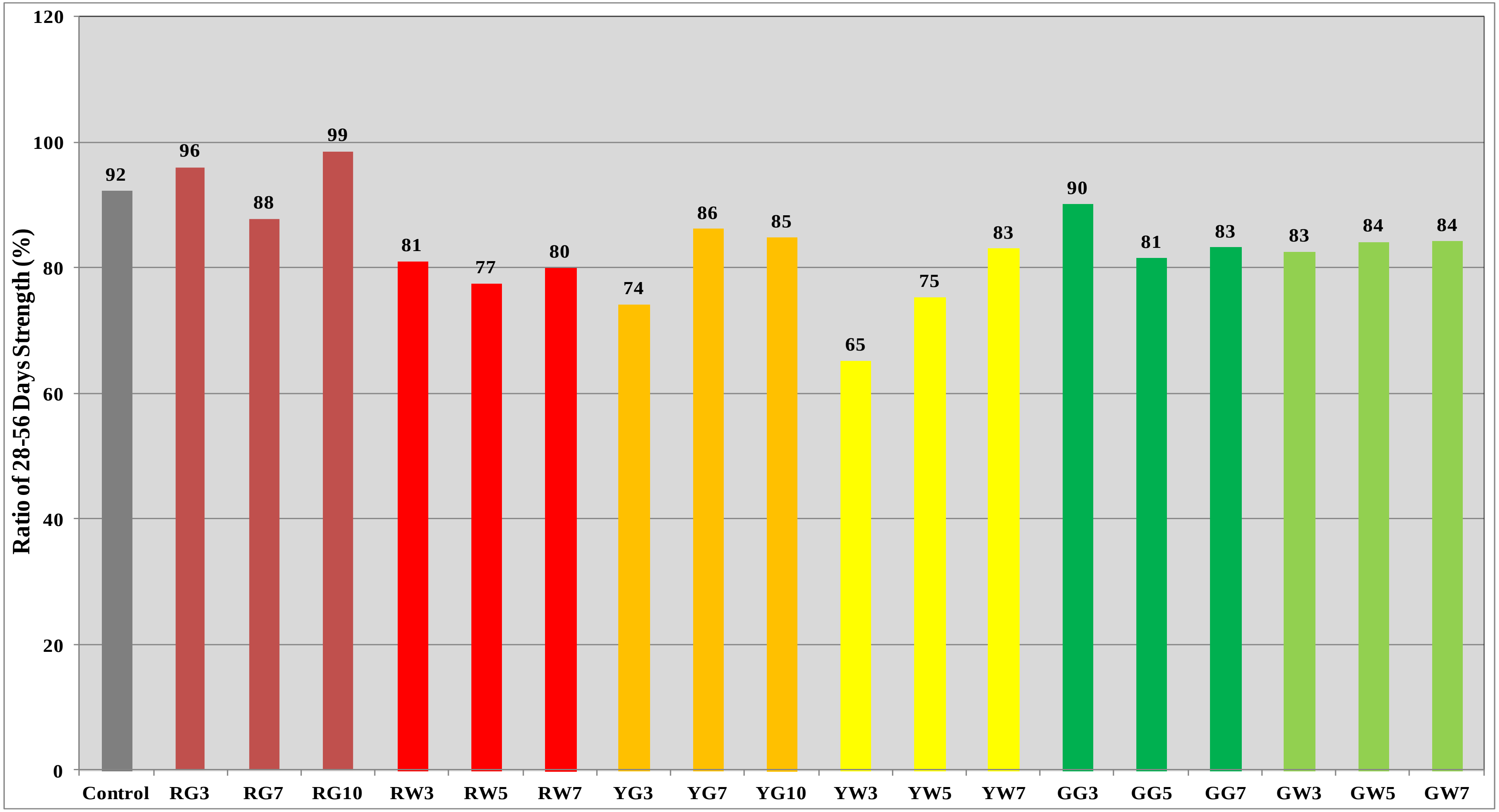

Figure 4.10 The Ratio between 28-Day and 56-Day Compressive Strength Results

4.2.2 Flexural Strength

The flexural strength results are listed in Table 4.3, and illustrated in Figures 4.11. The results ranged from 3.99 to 8.28 MPa, which present an acceptable difference between the two tested groups.

From Figure 4.11, it can be observed that the type of cement had a considerable effect on flexural strength results. The results ranged between 6.07-8.28 MPa and 3.99-5.39 MPa for pigmented grey mixtures and pigmented white mixtures respectively.

The relationship between flexural strength and the 28-day compressive strength is illustrated as a ratio pattern in Figure 4.12. The ratio is in the range of 20-34% and 20-32% for pigmented grey mixtures and pigmented white mixtures respectively.

The Egyptian Code of Practice asserts that the flexural strength of concrete can be expressed as a function of compressive strength according to the general equation:

$$\text{Estimated Flexural Strength} = 0.6 * \sqrt{f_{cu}} \qquad \text{(Eq.4.1)}$$

Figure 4.13 shows the ratio between experimental and estimated values of flexural to strength according to Eq.4.1. The ratio is in the range of 1.43-2.76 which presents an acceptable range and confirms the compliance of tested mixtures to the Egyptian Code of Practice. The increase in flexural strength values compared with compressive strength maybe attributed to the addition of different shaped pigments. This could have resulted in enhancing the interfacial between the aggregates and the binding cement that has often been the cause for flexural failure.

Table 4.3 28-Day Flexural Strength Results

Mix ID	Cement Type	Pigment Content (kg)	w/c	Flexural Strength (MPa)
Control	Ordinary Grey Cement	-	0.50	8.18
RG3	Ordinary Grey Cement	12	0.50	7.20
RG7	Ordinary Grey Cement	28	0.48	6.07
RG10	Ordinary Grey Cement	40	0.48	8.28
RW3	Ordinary White Cement	12	0.50	5.39
RW5	Ordinary White Cement	20	0.50	4.70
RW7	Ordinary White Cement	28	0.50	4.38
YG3	Ordinary Grey Cement	12	0.50	8.04
YG7	Ordinary Grey Cement	28	0.50	7.57
YG10	Ordinary Grey Cement	40	0.50	8.27
YW3	Ordinary White Cement	12	0.50	4.33
YW5	Ordinary White Cement	20	0.53	4.33
YW7	Ordinary White Cement	28	0.53	5.33
GG3	Ordinary Grey Cement	12	0.53	7.94
GG5	Ordinary Grey Cement	20	0.53	7.39
GG7	Ordinary Grey Cement	28	0.50	6.09
GW3	Ordinary White Cement	28	0.50	3.99
GW5	Ordinary White Cement	20	0.53	4.17
GW7	Ordinary White Cement	28	0.50	4.31

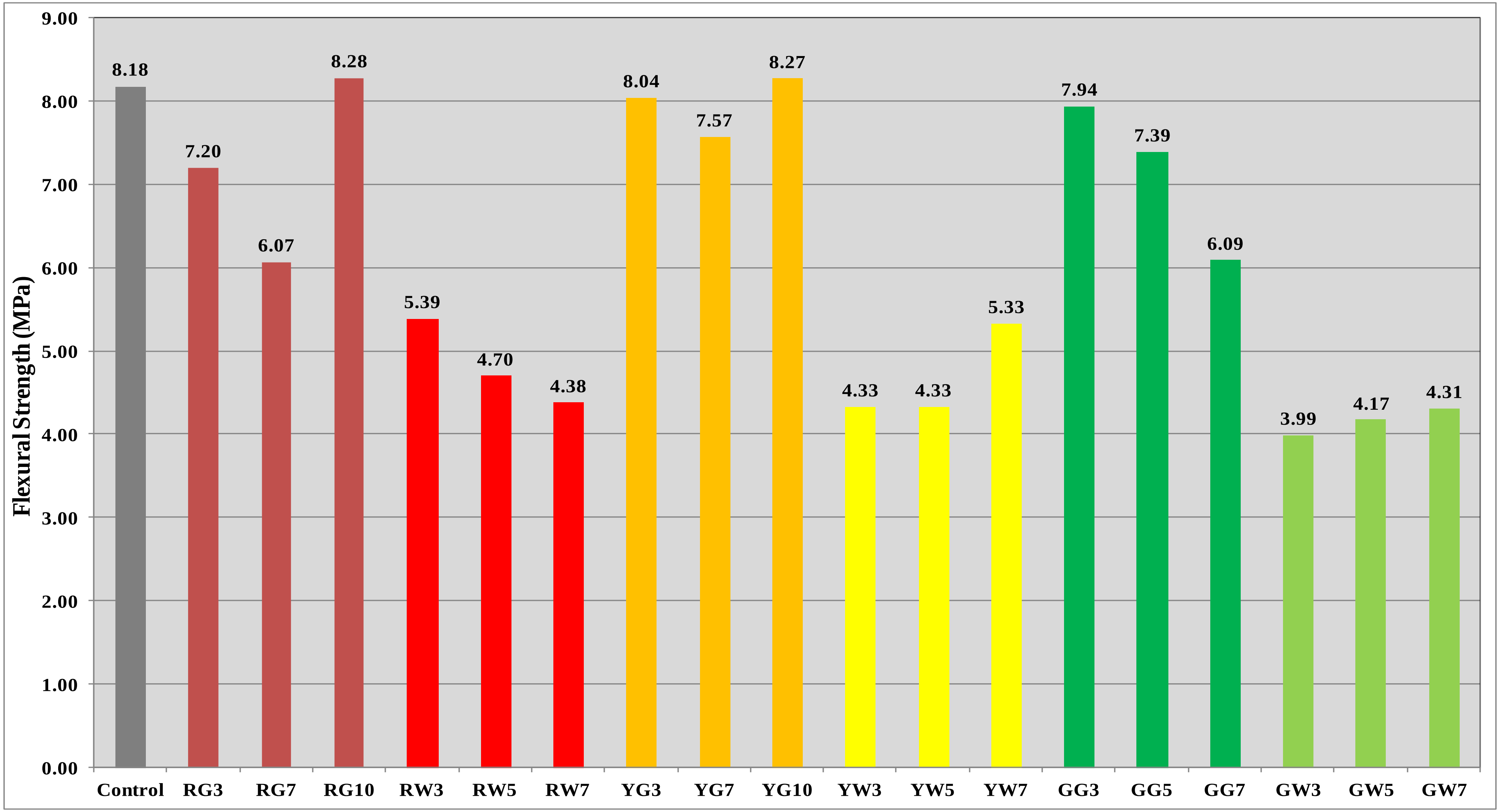

Figure 4.11 28-Day Flexural Strength Results

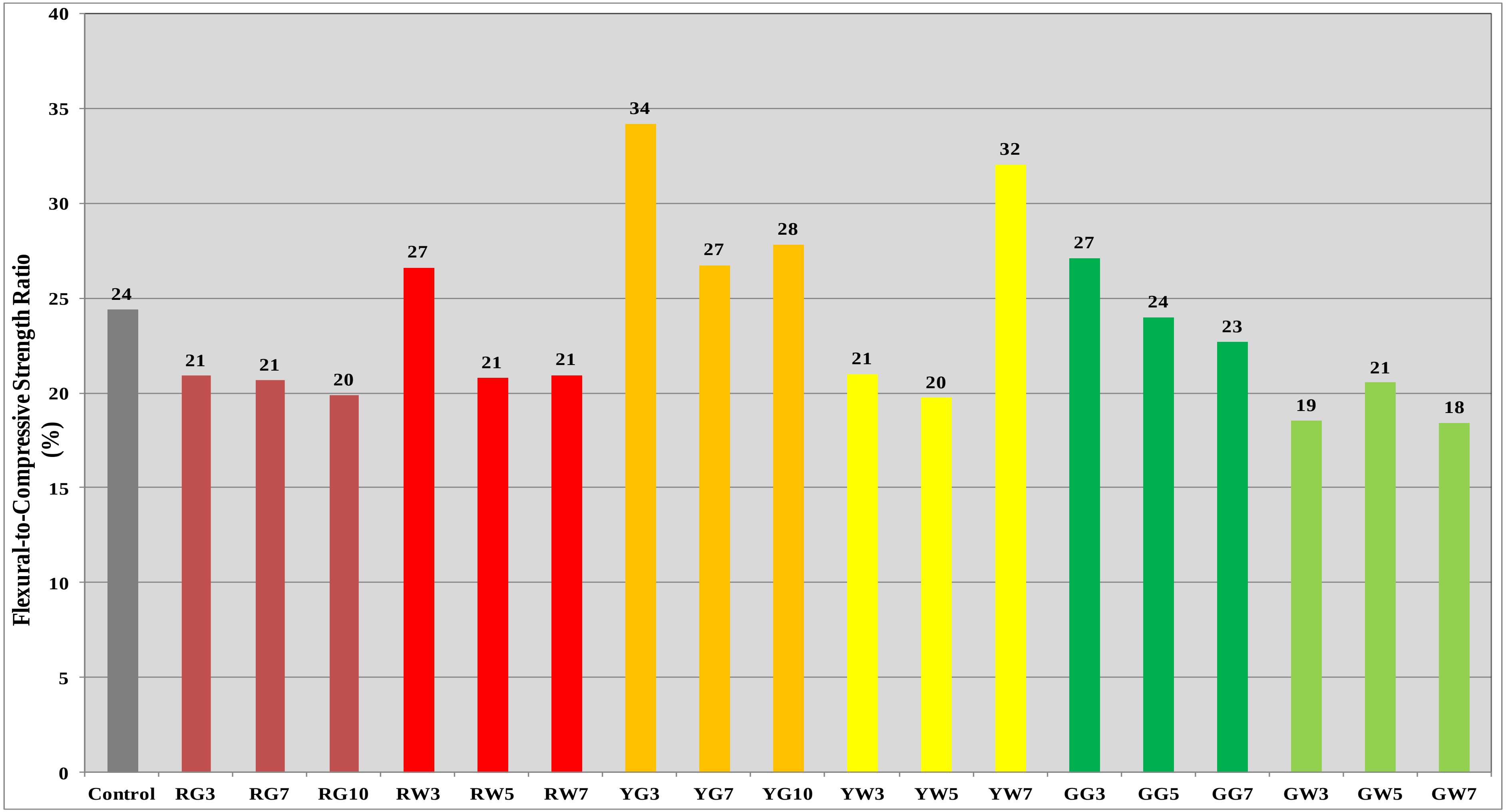

Figure 4.12 Ratio between 28-Day Flexural and Compressive Strength Results

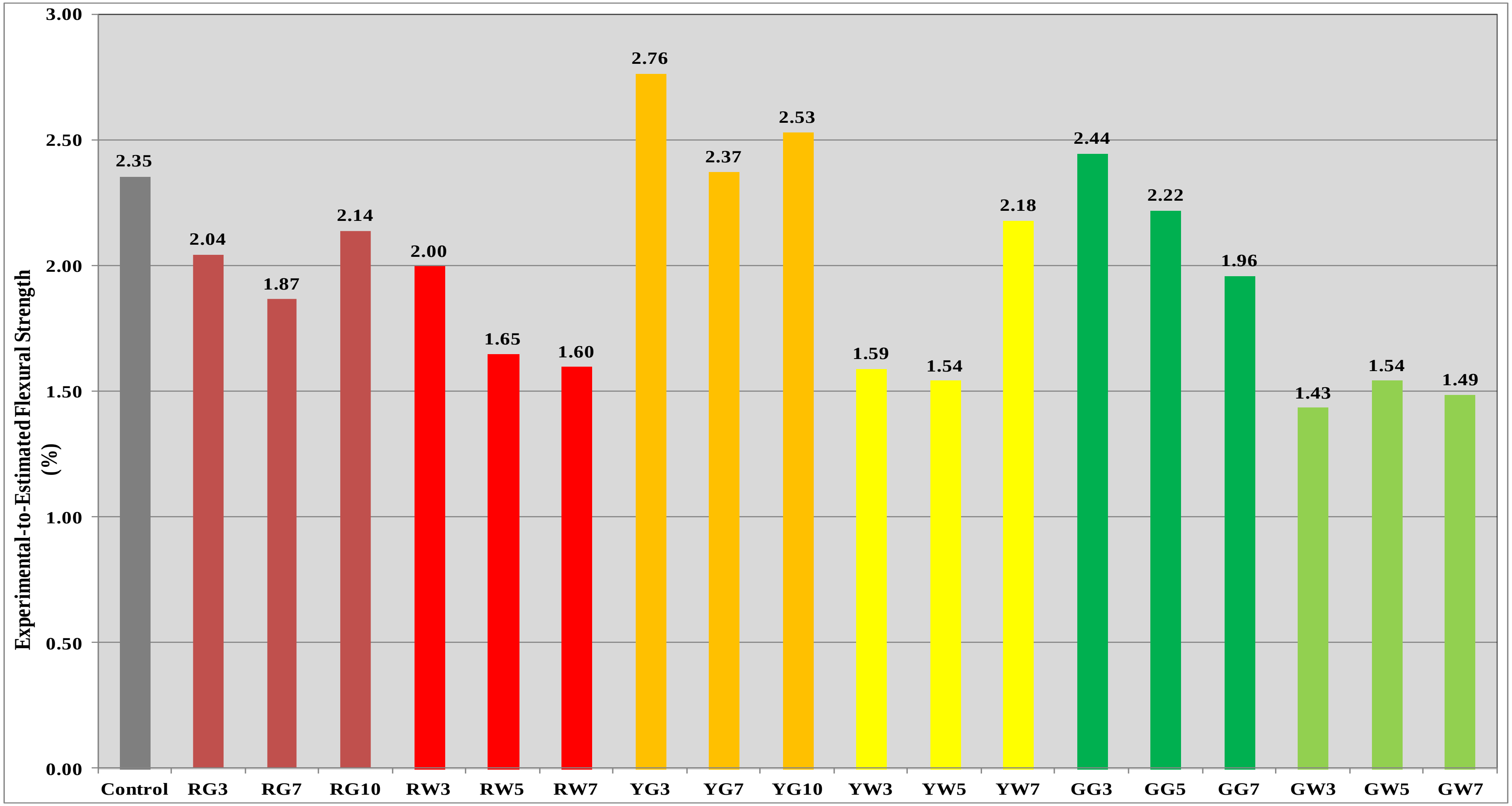

Figure 4.13 Ratio between Experimental and Estimated Flexural Strength Results Using Eq.4.1

4.2.3 Rapid Chloride Permeability Test (RCPT)

Rapid Chloride Permeability Test was conducted to evaluate concrete resistance to chloride penetration after 56 days. The results are listed in Table 4.4, and patterns are illustrated in Figures 4.15. The results ranged from 2676 to 6612 Coulombs, which indicate that chloride permeability class of the mixtures varied between moderate to high. From Figure 4.14 it can be observed that pigment type and dosage had a varying effect on passing charges when added to grey cement mixtures. The results ranged from 2676-4808 coulombs, 4491-5138 coulombs and 3554-6525 coulombs for red, yellow and green pigments respectively. A dosage of 3 percent red and yellow pigment by weight of cement resulted in lower passing charges than that of control unpigmented grey mixture. Increasing dosage to 7 percent resulted in a remarkable decrease in passing charges with red pigment but with no significant change with yellow pigment. Adding yellow pigment with maximum dosage of 10 percent resulted in a significant decrease in passing charges. Green pigment had inconsistent results than red and yellow pigments. While red and yellow pigments are composed mainly of iron oxides while green pigment is composed of chromium oxide. Adding a green pigment dosage of 3 percent to grey concrete resulted in significant reduction in passing charges, increasing the dosage to 5 percent resulted in a remarkable increase in passing charges surpassing the control grey cement with the maximum value of 6525 coulombs for pigmented grey cement mixtures. Finally, increasing dosage to 7 percent green pigment resulted in remarkable reduction in passing charges. Pigment dosage added to white cement mixtures had a consistent effect on passing charges. The results ranged from 3727-5708 coulombs, 3827-6612 coulombs and 3350-4327 coulombs for red, yellow and green pigments respectively.

Table 4.4 Rapid Chloride Permeability Results

Mix ID	Cement Type	Pigment Content (kg)	w/c	Average Passing Charges (Coulombs)
Control	Ordinary Grey Cement	-	0.50	5555
RG3	Ordinary Grey Cement	12	0.50	4808
RG7	Ordinary Grey Cement	28	0.48	2676
RG10	Ordinary Grey Cement	40	0.48	3128
RW3	Ordinary White Cement	12	0.50	3727
RW5	Ordinary White Cement	20	0.50	4481
RW7	Ordinary White Cement	28	0.50	5708
YG3	Ordinary Grey Cement	12	0.50	5068
YG7	Ordinary Grey Cement	28	0.50	5138
YG10	Ordinary Grey Cement	40	0.50	4491
YW3	Ordinary White Cement	12	0.50	3827
YW5	Ordinary White Cement	20	0.53	5707
YW7	Ordinary White Cement	28	0.53	6612
GG3	Ordinary Grey Cement	12	0.53	3554
GG5	Ordinary Grey Cement	20	0.53	6525
GG7	Ordinary Grey Cement	28	0.50	4440
GW3	Ordinary White Cement	28	0.50	4273
GW5	Ordinary White Cement	20	0.53	4327
GW7	Ordinary White Cement	28	0.50	3350

A dosage of 3 percent red and yellow pigment by weight of cement resulted in lower passing charges than that of control unpigmented grey mixture. Gradual increase of red and yellow pigment to dosage from 3 percent to 5 percent and 7 percent resulted in a gradual increase in passing charges. The maximum dosage of 7 percent resulted in higher passing charges than the control mixture. Green pigment resulted in more stable results when added to white cement mixtures. Adding a green pigment dosage of 3 percent resulted in slightly higher values of passing charges than red and yellow with the same dosage. Increasing the green pigment dosage to 5 percent had an insignificant effect on passing charges. While increasing dosage to 7 percent green pigment resulted in remarkable reduction in passing charges reaching a minimal value of 3350 coulombs for pigmented white cement mixtures.

From Figure 4.14, it can be observed that chloride permeability slightly decreased with lower water-to-cement ratio. For instance, mixture RG7 and RG10 had a w/c ratio of 0.48 resulting in the minimum values of passing charge of 2676 and 3128 coulombs respectively. This suggests that lower water-to-cement ratio generates denser concrete resulting in enhanced resistance to chloride ion penetration.

Rapid chloride permeability values were compared with 56-day compressive strength results. It was observed that grey concrete mixtures made with red and yellow pigments at the maximum dosage of 10 percent by weight of cement generally had minimum value of passing charges and maximum values of 56-day compressive strength results. It was also observed that a red pigment dosage of 7 percent resulted a minimum value of passing charges of 2676 coulombs and a compressive strength of 33.5 MPa , while a 7 percent yellow pigment dosage resulted in a high value of passing charges of 5138 coulombs and a compressive strength of 32.9 MPa. Green pigment showed a contradicting effect. A dosage of 5 percent green pigment resulted in the highest value of passing charges of 6525 coulombs had a compressive strength of 37.8 MPa. While green pigment dosages of 3 and 7 percent resulted in passing charges of 3554 and 4440 coulombs, and compressive strength of 32.5 and 32.3 MPa respectively. Permeability reduction in pigmented grey concrete is not in direct proportion with compressive strength increase suggesting that compressive strength is not an accurate chloride permeability indicator complying with Abou-Zeid et al (2003). Assessment of rapid chloride permeability values with 56-day compressive strength results of pigmented white concrete mixtures suggests different conclusion. It can be observed that red and yellow pigments added to white concrete mixtures with minimum dosage of 3 percent resulted in respective values of 25.0 and 31.6 MPa at 56-day compressive strength and minimum values of passing charges of 3727 and 3827 coulombs. While red and yellow pigments added to white concrete mixtures with maximum dosage of 7 percent resulted in minimum respective values of 26.2 and 20.1 at 56-day compressive strength and maximum values of passing charges of 5708 and 6612 coulombs. Adding green pigment to white concrete mixtures resulted in a proportional indication between compressive strength and passing charges. Green pigment dosage of 7 percent resulted in a maximum 56-day compressive strength of 27.8 MPa and minimum passing charges of 3350 coulombs while the pigment dosage of 3 percent resulted in a 56-day compressive strength of 26.1 MPa and passing charges of 4273 coulombs. Finally a pigment dosage of 5 percent resulted in a minimum 56-day compressive strength of 24.2 MPa and maximum passing charges of 4327 coulombs. It can be suggested that permeability reduction of pigmented white concrete is in direct proportion with compressive strength increase.

General comparison between values of passing coulombs of pigmented grey and white concrete with control unpigmented concrete suggest that pigments improve concrete resistance to chloride ion penetration. Although synthetic inorganic pigments

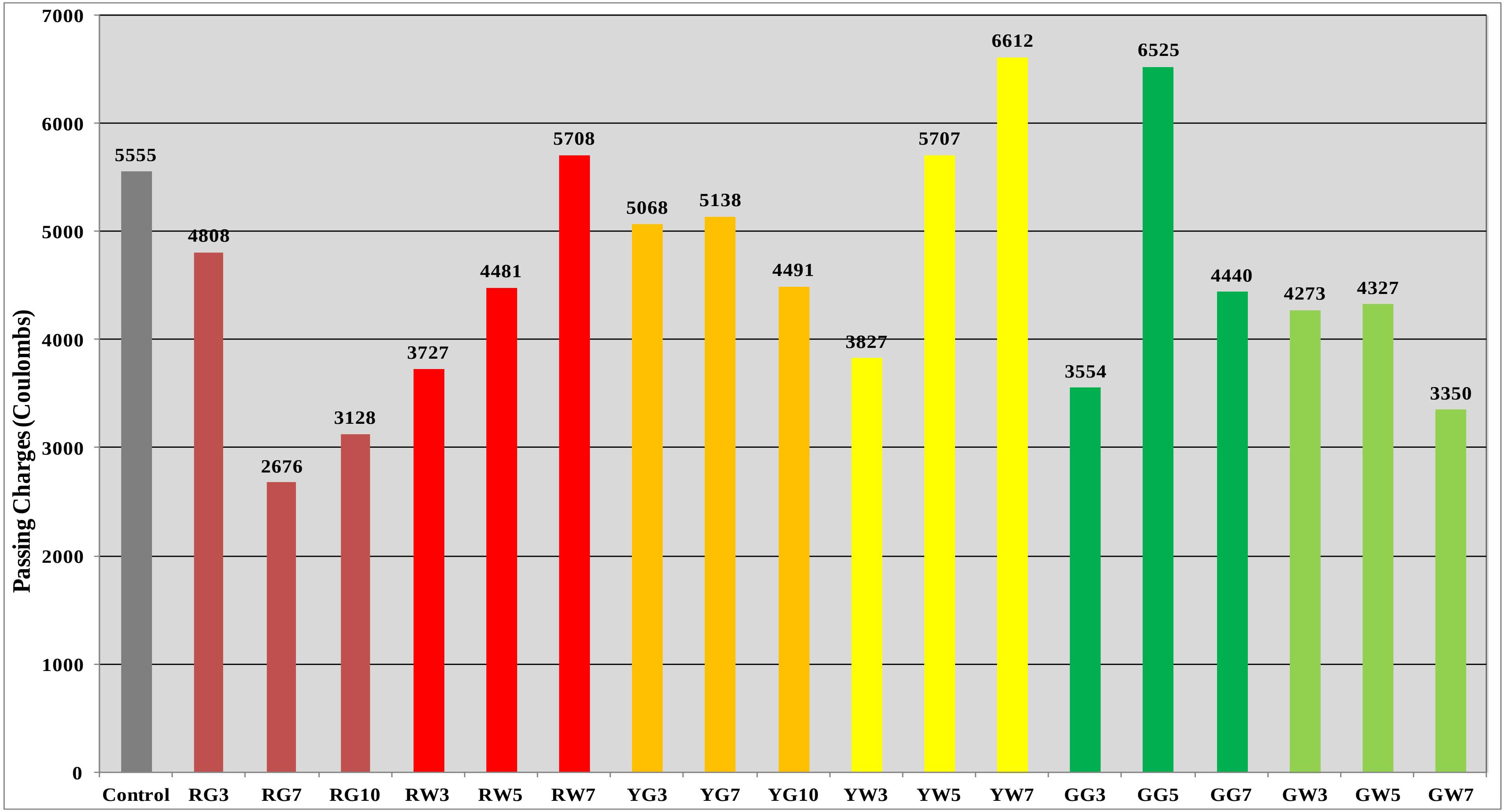

Figure 4.14 Rapid Chloride Permeability Results

used in this study are composed of very fine particles of metal oxides, results indicate that addition of pigments did not contribute to increasing the amount of electric charges passing through tested samples. Pigments may have increased the passing charges in RCPT test. However, this might be attributed to the conductivity effect and not permeability. That is perhaps why green chromium-oxide pigments had lower passing charges than red and yellow iron-oxide pigments.

4.2.5 Color Performance Monitoring by Digital Imaging

The color performance monitoring for pigmented concrete mixtures was carried out using digital imaging of hardened concrete specimens. Digital images were acquired at 7, 28 and 56 days and shown for each mixture in Appendix B. Digital images were computed to produce L*a*b* values, color saturation (C*) and total color difference (ΔE*) which were calculated according to Eq. 4.2 and Eq. 4.3 respectively (Lollini and Bertolini, 2013), (Lopez et al. 2009) and (Positieri and Helene, 2008). Results are listed in Tables 4.5, 4.6 and 4.7 for red, yellow and green pigments respectively. (ΔE*) is related to visual assessment i.e. human perception capabilities. A (ΔE*) value between 0.5 and 1.5 indicates slight difference in color hue. A value of 1.5 – 3.0 is an obvious difference, 3.0 – 6.0 is a very obvious difference and above 6.0 is a large difference (Lopez et al. 2009).

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad \text{Eq. 4.2}$$

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad \text{Eq. 4.3}$$

Color saturation patterns at 7, 28 and 56 days are illustrated in Figures 4.20, 4.21 and 4.22 respectively and digitally captured images are shown for separate mixtures in

Appendix B. Color saturation values for pigmented red mixtures ranged between 47.9-58.2, 31.8-51.9 and 43.2-57.3 at 7, 28 and 56 days respectively. Color saturation values for pigmented yellow mixtures ranged between 34.9-57.9, 32.0-49.1 and 33.2-48.4 at 7, 28 and 56 days respectively. Color saturation values for pigmented green mixtures ranged between 18.5-26.6, 17.8-30.9 and 15.0-28.2 at 7, 28 and 56 days respectively. Results indicate that for all pigmented mixtures, color appears brighter and more intense at the age of 7 days and changes into a darker color at 28 days. This might be attributed to the presence of hydration water at 28 days resulting in darker surface color. Overall color saturation results at 56 days for pigmented red and yellow mixtures indicate that color stabilized with higher color saturation values than those obtained at 28 days but with lower values than those obtained at 7 days. This complies with the findings of Positieri et al. (2008) and is shown in Figure 4.15. Green pigmented mixtures show a different trend after 56 days were color stabilizes with lower color saturation values than those obtained at 7 and 28 days as shown in Figure 4.16. Changes in color is a combined effect of numerous parameters including the following:

- Hydration of cement with time and the development of hydration product.
- Presence of water inside the mix.
- Wettability of the concrete surface.
- External atmospheric and weather conditions.

Thus, it can be concluded that color saturation values of pigmented grey and white concrete mixtures at different pigment dosages should be compared at 56 days after colors have stabilized. Overall results indicate that increasing pigment dosage increases color saturation for red, yellow and green pigments with both grey and white concrete mixtures.

Figure 4.15 Color saturation at 7, 28 and 56 days for mixtures RG7 and YG10

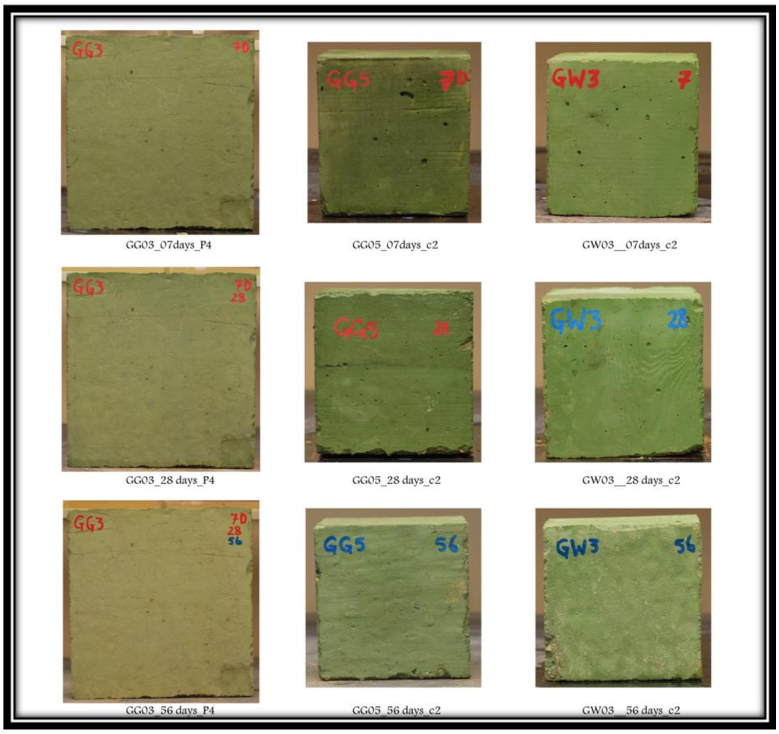

Figure 4.16 Color saturation at 7, 28 and 56 days for mixtures GG3, GG5 and GW3

Table 4.5 Color Performance Results for Pigmented Red Mixtures after 7, 28 and 56 Days

Mixture I.D.	Specimen Age (days)	L*	a*	b*	Color Saturation C*	Total Color Difference ΔE*
RG3	7	40.25	37.75	35.75	51.99	-
RG7	7	42.50	39.50	35.50	53.11	2.86
RG10	7	34.00	38.75	34.75	52.05	8.57
RW3	7	46.50	40.25	37.75	55.18	12.94
RW5	7	39.75	43.00	39.25	58.22	7.44
RW7	7	29.33	35.00	32.75	47.93	14.66
RG3	28	17.50	24.00	21.00	31.89	-
RG7	28	21.50	28.50	25.50	38.24	7.52
RG10	28	19.00	26.25	22.75	34.74	4.34
RW3	28	29.25	31.25	28.00	41.96	12.55
RW5	28	32.67	38.33	35.00	51.91	10.53
RW7	28	28.50	32.75	29.00	43.74	9.19
RG3	56	32.33	32.00	29.00	43.19	-
RG7	56	27.00	34.50	30.50	46.05	6.08
RG10	56	29.75	36.00	33.50	49.18	4.34
RW3	56	47.50	38.00	34.50	51.32	17.89
RW5	56	46.75	42.25	38.75	57.33	6.06
RW7	56	43.25	42.50	37.50	56.68	3.72

Table 4.6 Color Performance Results for Pigmented Yellow Mixtures after 7, 28 and 56 Days

Mixture I.D.	Specimen Age (days)	L*	a*	b*	Color Saturation C*	Total Color Difference ΔE*
YG3	7	40.25	12.75	32.50	34.91	-
YG7	7	36.00	14.25	35.75	38.49	5.56
YG10	7	49.75	16.25	45.75	48.55	17.12
YW3	7	53.75	17.00	49.00	51.87	5.21
YW5	7	54.50	18.25	52.25	55.35	3.56
YW7	7	54.50	19.00	54.75	57.95	2.61
YG3	28	33.00	12.50	29.50	32.04	-
YG7	28	49.25	15.25	43.25	45.86	21.46
YG10	28	29.50	14.00	32.75	35.62	22.40
YW3	28	52.75	15.00	41.75	44.36	24.95
YW5	28	51.00	16.25	44.00	46.90	3.11
YW7	28	53.00	16.50	46.25	49.11	3.02
YG3	56	52.00	11.00	31.33	33.20	-
YG7	56	51.33	13.67	40.00	42.27	9.10
YG10	56	52.33	14.33	43.00	45.32	3.23
YW3	56	51.67	14.33	40.67	43.12	2.42
YW5	56	49.00	16.33	43.67	46.62	4.49
YW7	56	50.00	17.00	45.33	48.41	2.05

Table 4.7 Color Performance Results for Pigmented Green Mixtures after 7, 28 and 56 Days

Mixture I.D.	Specimen Age (days)	L*	a*	b*	Color Saturation C*	Total Color Difference ΔE*
GG3	7	32.00	-1.50	18.50	18.56	-
GG5	7	33.25	-4.50	20.50	20.99	3.82
GG7	7	26.50	-4.00	19.00	19.42	6.93
GW3	7	40.75	-5.25	25.00	25.55	15.51
GW5	7	25.50	-6.75	21.75	22.77	15.66
GW7	7	30.25	-9.75	24.75	26.60	6.37
GG3	28	49.50	-1.25	17.75	17.79	-
GG5	28	36.25	-6.50	21.75	22.70	14.80
GG7	28	47.25	-5.50	22.00	22.68	11.05
GW3	28	45.25	-9.25	25.75	27.36	5.67
GW5	28	42.25	-13.00	28.00	30.87	5.30
GW7	28	39.25	-12.50	27.25	29.98	3.13
GG3	56	46.00	-0.67	15.00	15.01	-
GG5	56	44.67	-5.00	18.67	19.33	5.83
GG7	56	45.33	-4.00	19.33	19.74	1.37
GW3	56	46.33	-6.33	22.00	22.89	3.68
GW5	56	48.00	-8.33	22.67	24.15	2.69
GW7	56	46.33	-11.00	26.00	28.23	4.58

As explained earlier in Chapter 3, saving image files after RAW correction procedure in *.PSD or *.TIFF file formats permits future measurements of L*, a* and b* color parameters with the same results. Though it is crucial to use the same platform and Adobe Photoshop software version since the process is device dependant.

At 56 days color saturation values of red pigmented grey concrete ranged between 43.2-49.2 at a dosage of 3 and 10 percent red pigment respectively. Mixture RG10 resulted in the maximum tinting value for red pigment with grey concrete. This might be attributed to a lower tinting strength of red pigment as indicated by NCMA (2002). While addition of red pigment to white concrete resulted in values ranging between 51.3-56.7 at a dosage of 3 and 7 percent respectively at 56 days. Mixture RW5 resulted in a color saturation value of 57.3 which is higher than RW7 color saturation value of 56.7 indicating a saturation point at 5 percent dosage as shown in Figure 4.17. Saturation point is reached when increasing pigment dosage fails to produce a noticeable difference in color saturation (Weber et al. 2009).

Figure 4.17 Color Saturation for Mixtures RW7 and RW5

At 56 days, adding yellow pigment to grey concrete resulted in color saturation values ranging between 33.2-45.3 at a dosage of 3 and 10 percent respectively. Mixture YG10 resulted in the maximum tinting value for yellow pigment with grey concrete indicating its low tinting strength when added to grey concrete. It is not recommended to use grey cement when light or buff tones are desired as indicated by NCMA (2002). Addition of yellow pigment to white concrete resulted in values ranging between 43.1-48.4 at a dosage of 3 and 7 percent respectively at 56 days. While mixture YW5 resulted in a color saturation value of 46.6 indicating a saturation point at 5 percent dosage. Results show that the minimum dosage of yellow pigment produces a vivid pastel color with white cement. This is further shown with color saturation values of 45.3 and 43.1 resulting for mixtures YG10 and YW3 as shown in Figure 4.18. While a 10 percent maximum dosage resulted in a better saturation with grey cement, a minimal dosage of 3 percent added to white cement produced a more vivid color.

Figure 4.18 Color Saturation for Mixtures YG10 and YW3

At 56 days, adding green pigment to grey concrete resulted in color saturation values ranging between 15.0-19.7 at a dosage of 3 and 7 percent respectively. Mixture GG5 resulted in a color saturation value of 19.3 indicating a saturation point at 5 percent dosage, when added to grey concrete. Results show that green pigment produces acceptable color saturation values when added to grey cement even at the minimum dosage as seen in Figure 4.19. This has an economical aspect as chromium oxide green pigment price is three times higher price than red and yellow iron oxide pigments. While addition of green pigment to white concrete resulted in values ranging between 22.9-28.2 at a dosage of 3 and 7 percent respectively at 56 days. While mixture GW7 resulted in a maximum color saturation value of 28.2 indicating a saturation point at 7 percent dosage, results indicate that a minimum dosage of green pigment produces a vivid and acceptable pastel color with white cement.

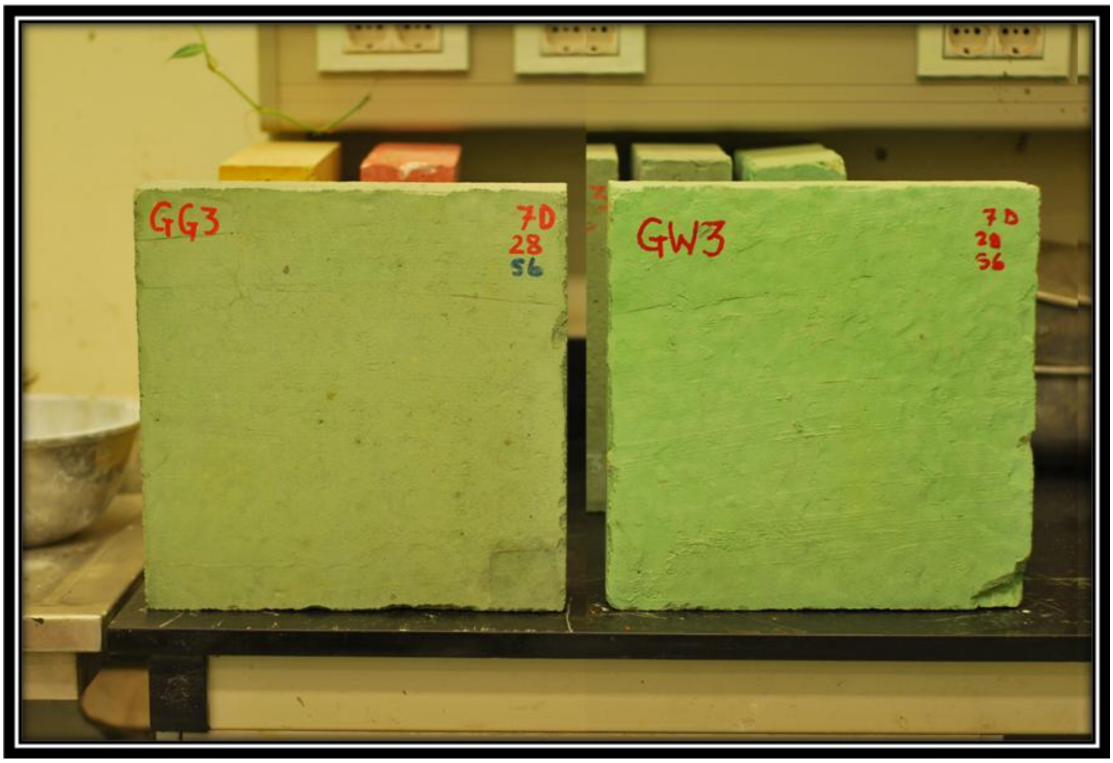

Figure 4.19 Color Saturation for Mixtures GG3 and GW3

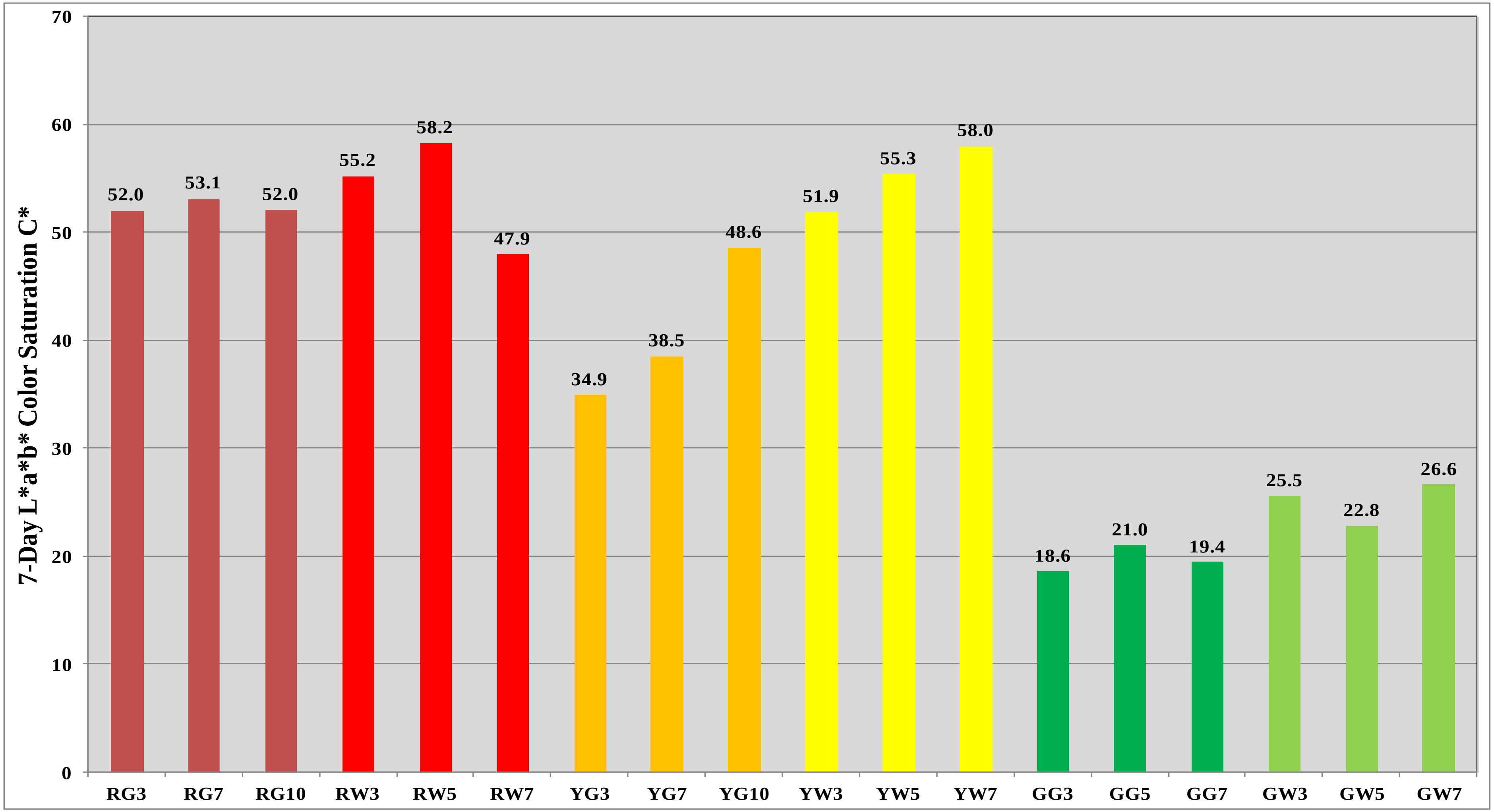

Figure 4.20 7-days Color Saturation (C*) Results

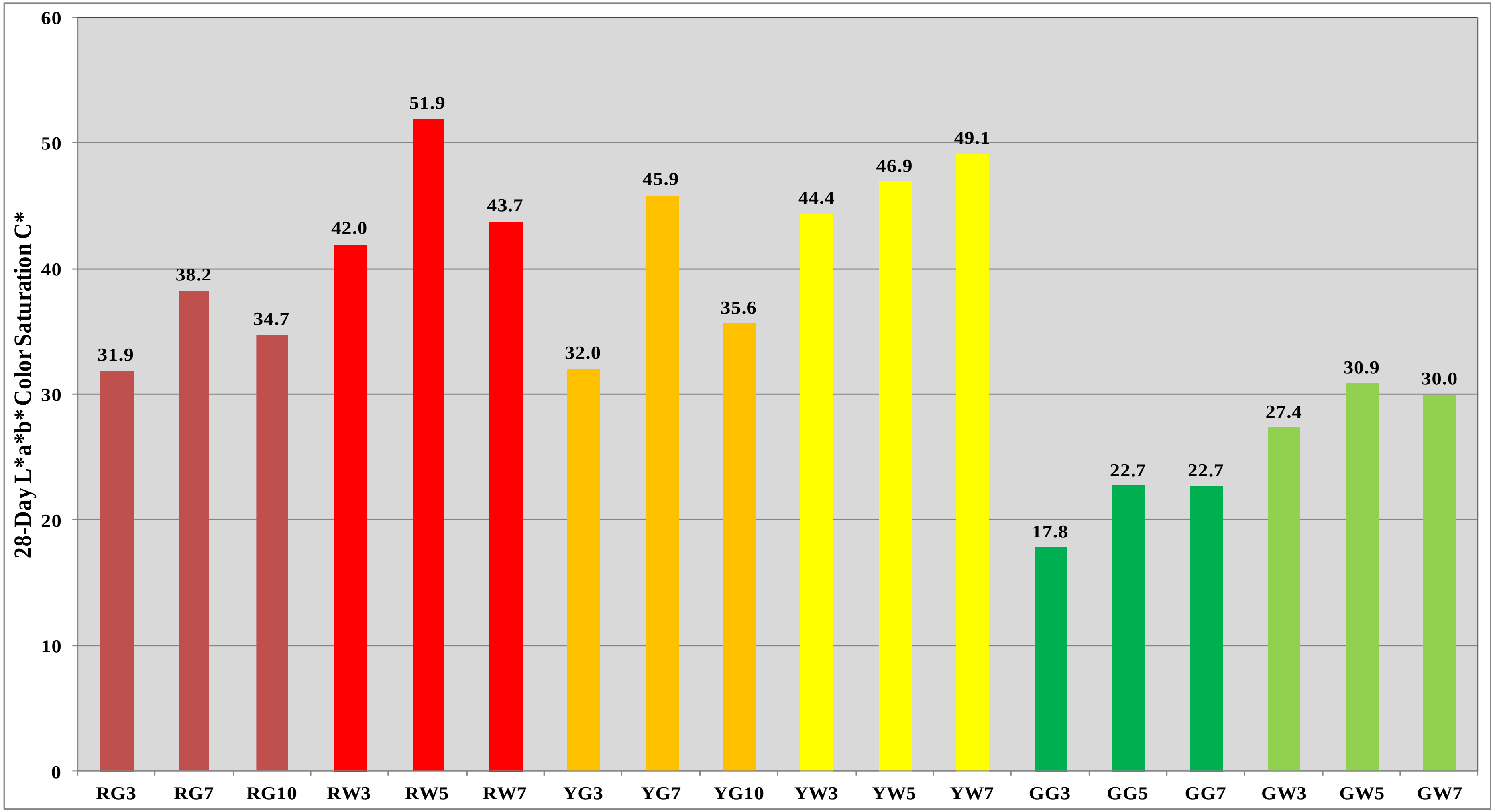

Figure 4.21 28-days Color Saturation (C*) Results

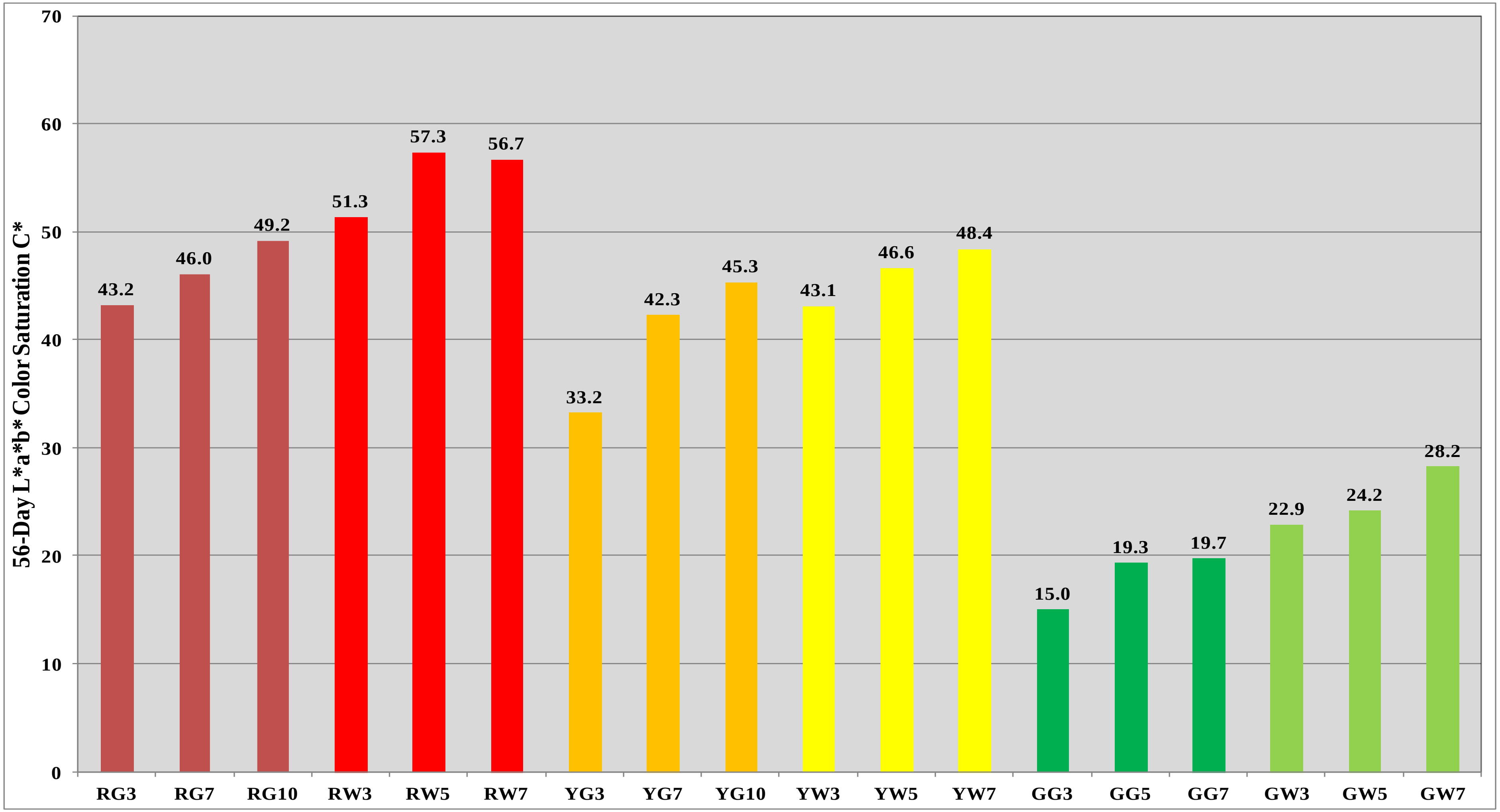

Figure 4.22 56-days Color Saturation (C*) Results

Total color difference (ΔE^*) was calculated according to Eq. 4.3 as the Euclidian distance between two points in the $L^*a^*b^*$ color space representing consecutive pigment dosages of red, yellow and green pigments. It was also calculated between the highest dosage of pigmented grey concrete and the proceeding minimum dosage of pigmented white concrete for all mixtures. (ΔE^*) patterns at 7,28 and 56 days are illustrated in Figures 4.23, 4.24 and 4.25 respectively.

(ΔE^*) values for pigmented red mixtures ranged between 2.9-12.9, 4.3-12.5 and 3.7-17.9 at 7, 28 and 56 days respectively. (ΔE^*) values for pigmented yellow mixtures ranged between 2.6-17.1, 3.0-25.0 and 2.0-9.1 at 7, 28 and 56 days respectively. (ΔE^*) values for pigmented green mixtures ranged between 3.8-15.6, 3.1-14.8 and 1.4-5.8 at 7, 28 and 56 days respectively. Total color difference values were further assessed at 56 days after colors have stabilized as indicated by minimal values of (ΔE^*) with changing of pigment dosages.

For red pigmented mixtures a minimum (ΔE^*) of 3.7 was calculated between mixtures RW7 and RW5 confirming the saturation point at 5 percent dosage. While a maximum (ΔE^*) of 17.9 was calculated between RG10 and RW3 indicating a wide color difference between the resulting color using a maximum dosage of red pigment with grey cement compared with the minimum dosage of red pigment with white cement as shown in Figure 4.26. This is attributed to the wide difference in L^* values ranging between 29.7 and 47.5 for RG10 and RW3 respectively. This indicates the effect of Lightness (L^*) value from red pigmented grey cement mixtures to red pigmented white cement mixtures.

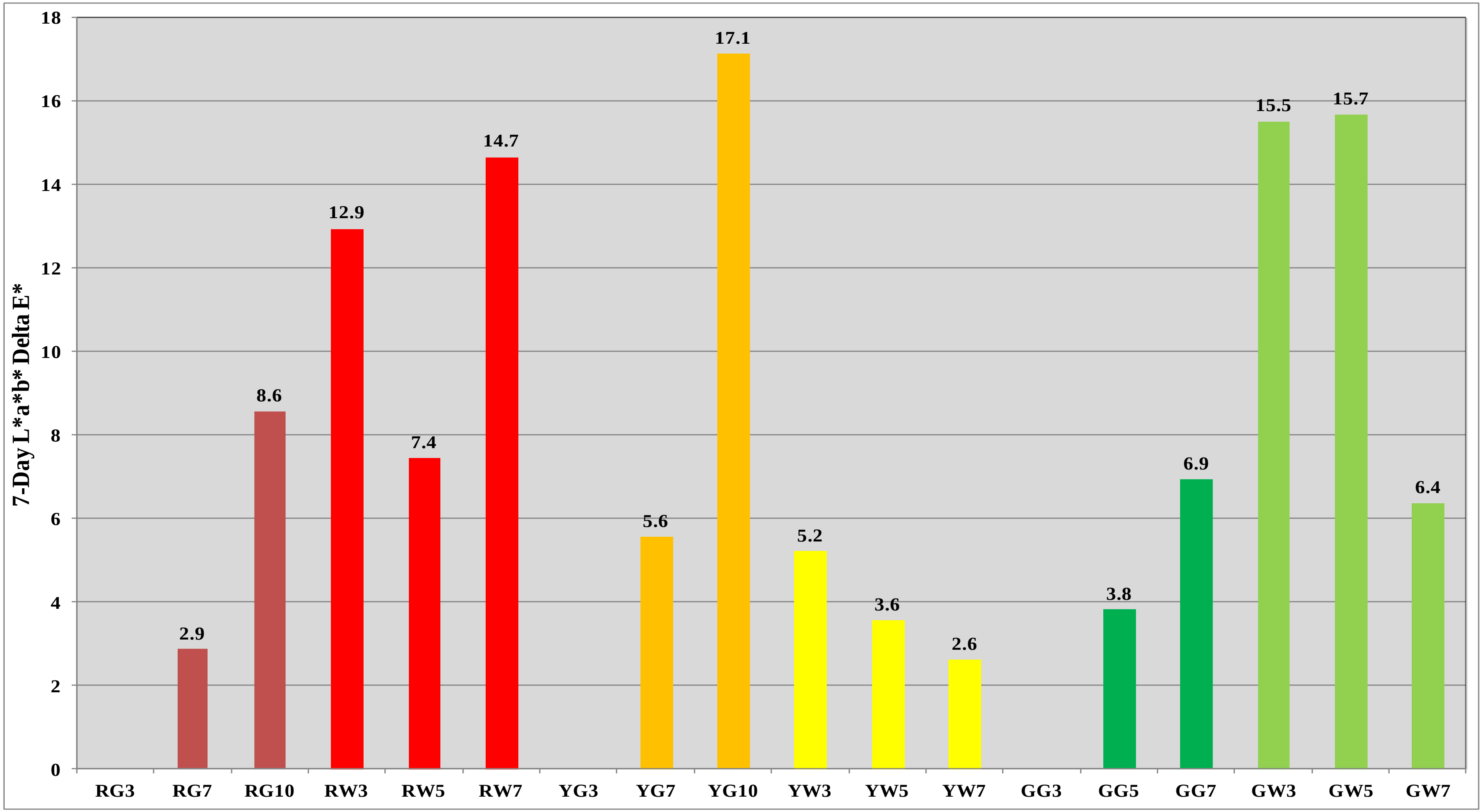

Figure 4.23 7-days Total Color Difference (ΔE*) Results

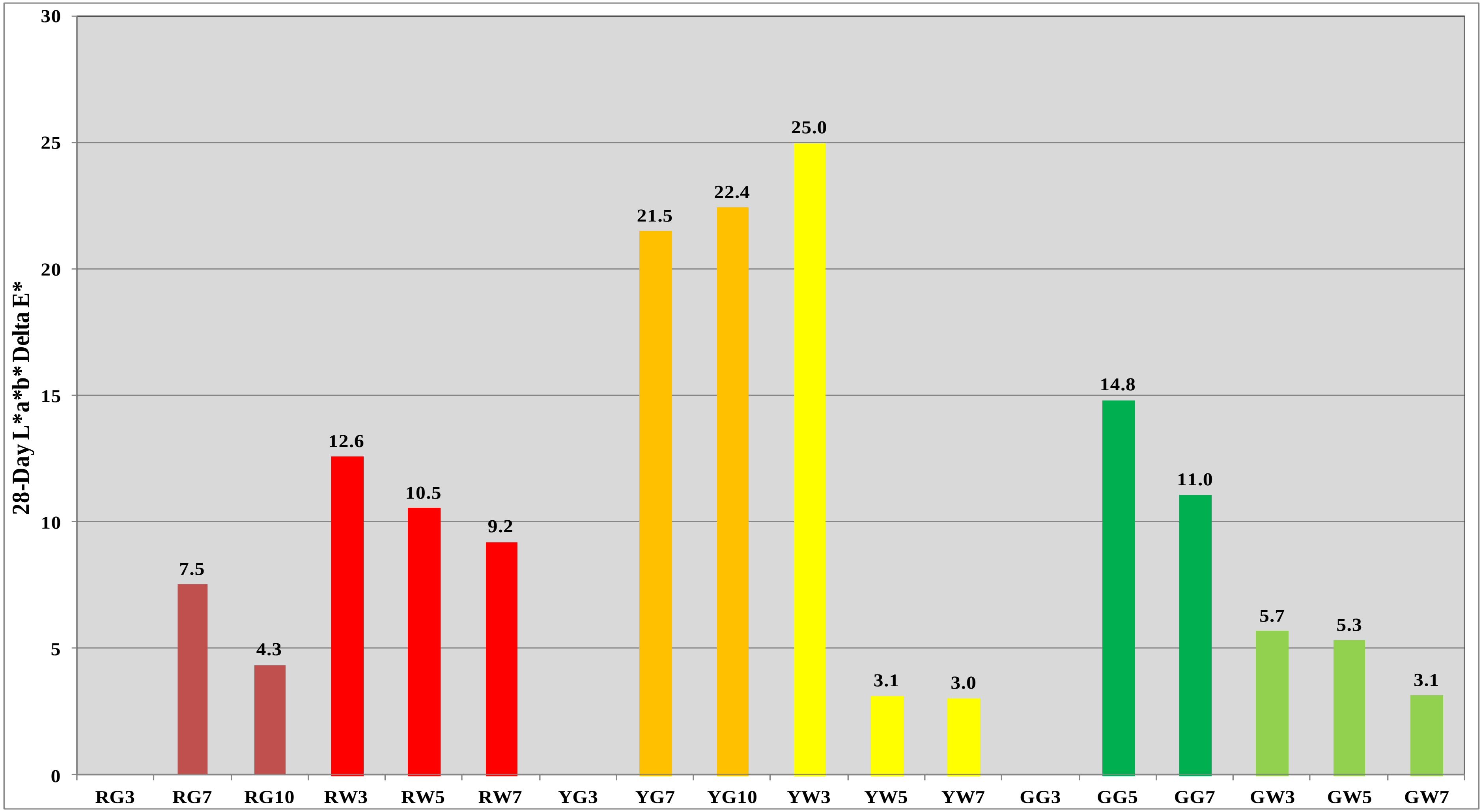

Figure 4.24 28-days Total Color Difference (ΔE*) Results

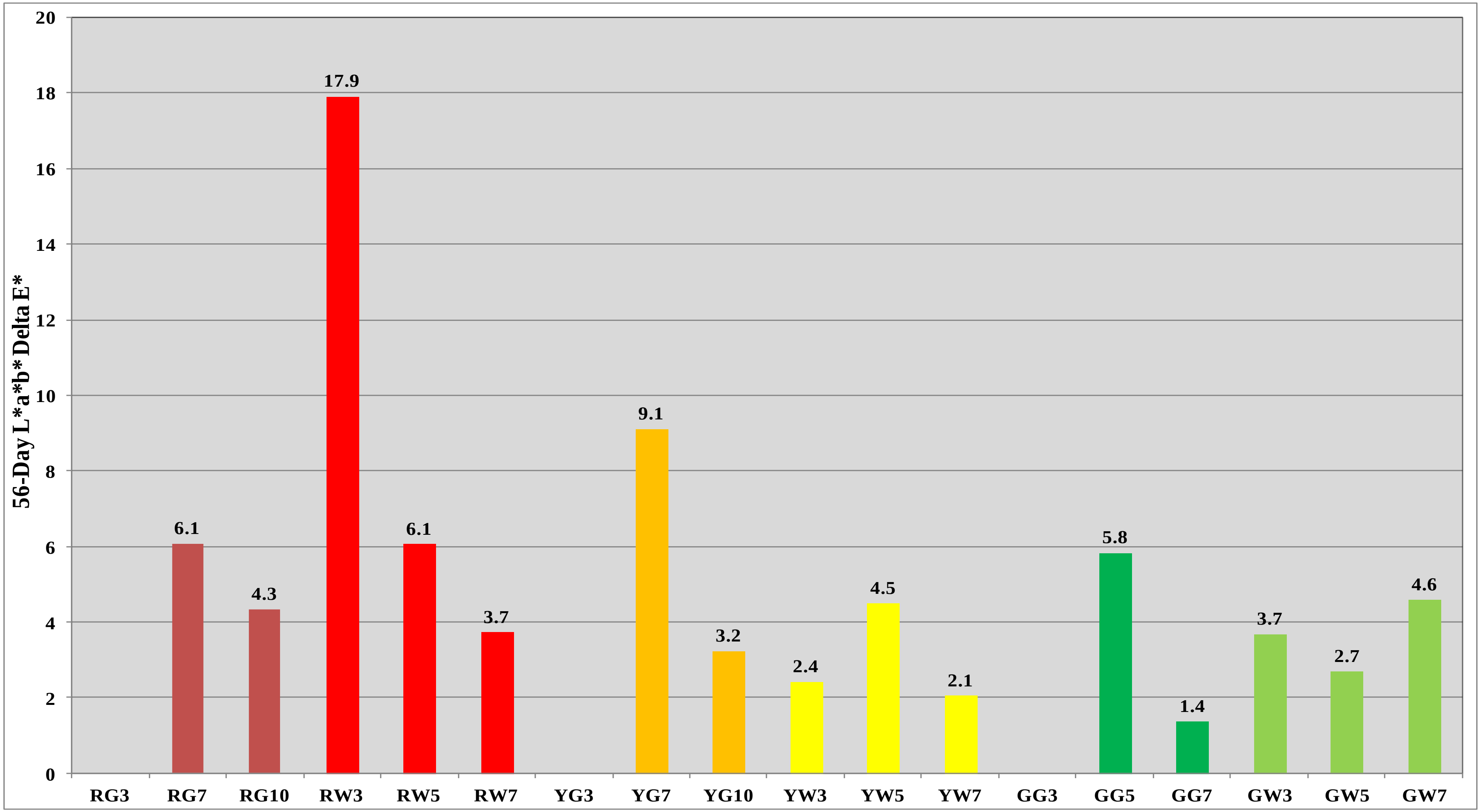

Figure 4.25 56-days Total Color Difference (ΔE*) Results

Figure 4.26 Color Saturation for Mixtures RG10 and RW3

For yellow pigmented mixtures a minimum (ΔE*) of 2.0 was calculated between mixtures YW7 and YW5 as shown in Figure 4.27 while (ΔE*) value of 4.5 was calculated between mixtures YW5 and YW3 confirming the saturation point at 5 percent dosage. While a maximum (ΔE*) of 9.1 was calculated between YG7 and YG3 as shown in Figure 4.28. This might be attributed to the darkening effect of grey cement with minimum dosage of yellow pigment resulting in a greenish tint that was further lightened when yellow pigment dosage was increased to 7 percent. Overall, the lower values of (ΔE*) between different yellow pigments dosages added to white concrete further show that more vivid colors are produced with white cement than with grey cement.

Figure 4.27 Color Saturation for Mixtures YW5 and YW7

Figure 4.28 Color Saturation for Mixtures YG3 and YG7

For green pigmented grey concrete mixtures a minimum (ΔE*) of 1.4 was calculated between mixtures GG7 and GG5 which is a slight, visually undetectable difference according to Lopez et al. (2009) and is shown in Figure 4.29. A maximum (ΔE*) value of 5.8 was calculated between mixtures GG5 and GG3 confirming the saturation point at 5 percent dosage. This might be attributed to the coloring effect of grey cement that has contributed to the greening effect of pigment at a moderate dosage. For green pigmented white concrete mixtures a minimum (ΔE*) of 2.7 was calculated between mixtures GW5 and GW3 while a maximum (ΔE*) value of 4.6 was calculated between mixtures GW7 and GW5 confirming the saturation point at 7 percent dosage. Overall, the lower values of (ΔE*) between different green pigments dosages added to white concrete further show that more vivid colors are produced with white cement than with grey cement.

Figure 4.29 Visual Difference (ΔE*) for mixtures GG7 and GG5

4.2.6 Visual Color Assessment

Visual color comparisons were carried out after 56 days. Hardened concrete slab specimens 300 x 300 x 80 mm made with the same pigment were set together to permit visual comparisons of the coloring effect of pigment.

Red pigments exhibited varying effects when added to grey cement. Addition of red pigment with a minimum dosage of 3 percent produced an uneven color distribution. Increasing red pigment dosage to 7 percent resulted in an acceptable uniform color with no visible defects, while the maximum dosage of 10 percent exhibited an enhanced vivid red pigmented grey concrete despite being uneconomical. Visual difference in color saturation between RG7 and RG10 suggests that saturation point can be reached at a dosage between 7 and 10 percent as shown in Figure 4.30. Adding a dosage 3 percent red pigment to white concrete also resulted in an uneven color with visible traces of unmasked white cement. Increasing pigment dosage to 5 percent resulted in a vivid paste shade while using a maximum dosage of 7 percent showed a slightly enhanced red pigmentation indicating that saturation point is reached at 5 percent dosage with white cement. Overall visual assessment shows that red pigment can be added to both grey and white cement to produce aesthetically appealing red concrete complying with the findings of NCMA (2002) and with the results of color performance using digital imaging technique.

Addition of yellow pigment at a minimum dosage of 3 percent to grey cement produced an aesthetically unappealing greenish yellow color indicating a weak masking effect that is attributed to the dominating color of grey cement. Increasing yellow pigment dosage to 7 percent resulted in an improved yellowish green color

Figure 4.30 Color Saturation for Mixtures RG10 and RG7

that is also unappealing aesthetically as shown in Figure 4.31. While the maximum dosage of 10 percent exhibited an enhanced yellow pigmented grey concrete despite being uneconomical. Adding a dosage 3 percent yellow pigment to white concrete resulted in a visually acceptable color though white cement was not completely masked. Color is further enhanced with dosage increase to 5 and 7 percent. Almost no visual color difference was detected between mixtures YW5 and YW7 indicating a saturation point is reached at 5 percent dosage. Visual assessment shows that it is not recommended to use yellow pigment with grey cement due to its low tinting strength complying with the findings of NCMA (2002). Adding yellow pigment to white cement generally results in a vivid, aesthetically appealing concrete which is also asserted with color performance results using digital imaging technique.

Figure 4.31 Color Saturation for Mixtures YG3 and YG7

Addition of green pigment at a minimum dosage of 3 percent to grey cement produced an aesthetically appealing color indicating a compatibility between the grey color of cement with chromium green color. Increasing green pigment dosage to 5 percent resulted in an improved green color while the maximum dosage of 7 percent resulted in an undetectable color change indicating a saturation point reached at 5 percent dosage with grey cement. Adding a dosage 3 percent green pigment to white concrete resulted in an uneven color with visible traces of unmasked white cement. Green color is further enhanced with dosage increase to 5 then 7 percent producing a vivid shades of green with white cement as shown in Figure 4.32. A better pigmented green color was achieved at 7 percent dosage indicating the saturation point with white cement which was also asserted with color performance results using digital imaging technique. This further indicates the contributing effect of grey cement to green pigmentation resulting in lower saturation point with mixture GG5 than that reached with white cement mixture GW7. Overall visual assessment shows that green pigment can be added to both grey and white cement to produce aesthetically appealing green concrete though a more lively color is achieved with white cement.

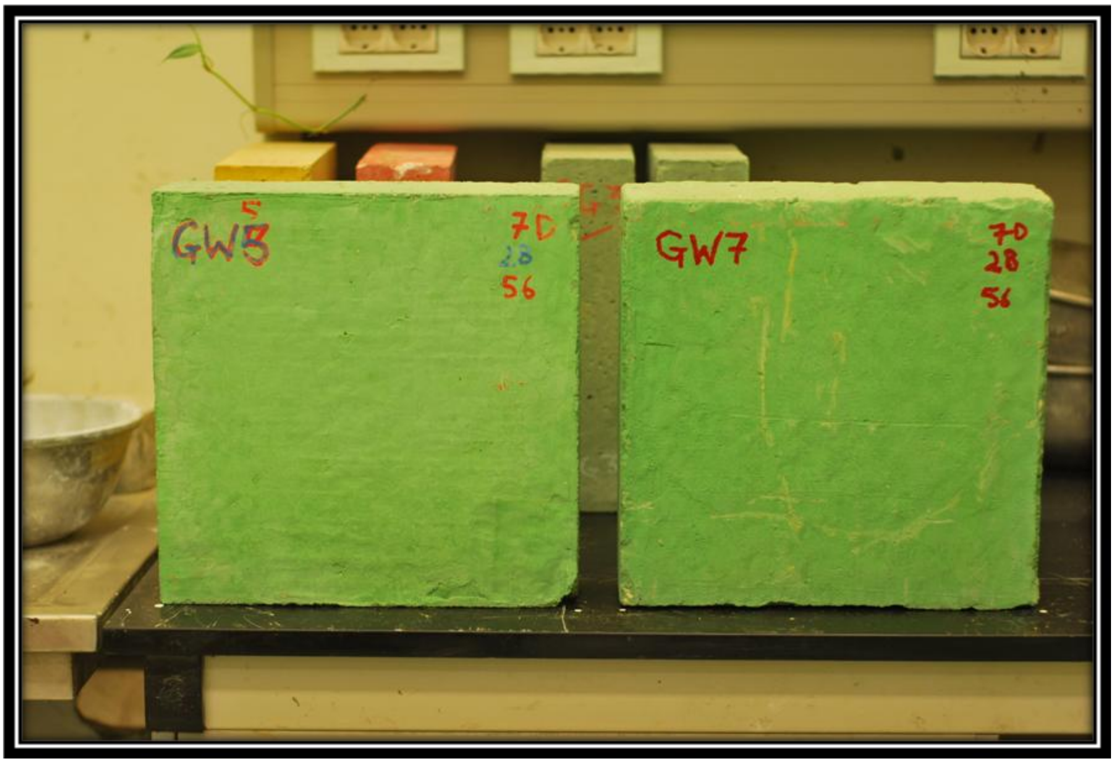

Figure 4.32 Color Saturation for Mixtures GW5 and GW7

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the materials, procedures, construction techniques and other parameters associated with this work, the following conclusions and recommendations are stated:

- Addition of the red and yellow pigments to grey concrete mixtures decreased slump as pigment dosage increased while addition of the green pigment to grey concrete increased slump with dosage increase.
- Addition of red, yellow and green pigments to white concrete mixtures show inconsistent slump results.
- Overall, pigment type and dosage did not have a significant impact on air content nor unit weight.
- Red and yellow pigmented grey concrete mixtures yielded somewhat higher air content than red and yellow pigmented white concrete mixtures.
- With the exception of red pigmented grey concrete, addition of all pigments introduced a decrease in compressive strength at 7 days. Much of the drop in compressive strength at 7 days was recovered after 28 and 56 days.
- Pigmented white concrete mixtures showed a higher decrease in compressive strength at 7 days compared with pigmented grey concrete mixtures.
- Average drop in compressive strength of pigmented mixtures ranged between 10 to 20 percent. Thus, the strength of most pigmented mixtures in this work allows their use in structural applications.

- Adding the maximum pigment dosage of 10 percent of red and yellow to grey concrete mixtures resulted in the highest compressive strength results.
- Overall, the increase in pigment dosage did not result in a well defined strength pattern.
- While experimental mix design aimed at a compressive strength of 30 MPa for both grey and white pigmented concrete mixtures, a minimum of 25 MPa was achieved with pigmented white mixtures which represents the lower boundary of structural concrete without using admixtures.
- Addition of pigments did not exhibit an effect on flexural strength results compared with unpigmented grey control mix.
- Pigmented white concrete mixtures showed a decrease in flexural strength results than pigmented grey concrete mixtures suggesting an effect of cement type.
- The experimental flexural strength results for pigmented concrete mixtures are closer to the values estimated by the Egyptian Code of Concrete.
- RCPT results suggest that pigmented concrete mixtures varied between moderate to high chloride permeability class according to test standards. However, This may be attributed to conductive properties of metal oxide pigments and not necessarily permeability.
- Compared with grey unpigmented control mixture, increasing dosage of iron oxide red and yellow pigments to grey concrete decreased the passing coulombs. While increasing red and yellow pigments to white concrete increased the passing coulombs.
- Adding chromium oxide green pigments to both grey and white concrete resulted in an overall decrease in passing coulombs compared with

unpigmented control mix. This suggests the difference in conducting properties of chromium oxide green and iron oxide red and yellow pigments.

- Overall results suggest that pigments improved resistance to chloride ion penetration. While pigmented mixtures with minimum water to cement ratio also exhibited lower permeability, results show that mixtures with lower permeability is generally not correlated with higher compressive strength results.
- A technique was developed for the assessment of the degree of pigmentation and pigment stability with time. This technique is repeatable and can be used for concrete surfaces in general with good reliability.
- Overall results show that increasing pigment dosage results in better color, however the mechanical performance and economy might be affected. However, Color saturation values of pigmented grey and white concrete mixtures at different pigment dosages should be compared after 56 days to ensure cement hydration is complete and concrete color stabilized.
- Visual analysis and calculations using digital imaging suggests that saturation point exists at a dosage between 7 and 10 percent for red pigmented grey concrete, while only 5 percent dosage was needed for green pigmented grey concrete. This is attributed to the contribution of the grey cement color to the greening effect of chromium oxide pigment.
- With the exception of yellow pigmented grey concrete, a saturation point was reached for red, yellow and green pigments used with grey and white concrete mixtures. Saturation point was reached at a dosage of 5 percent of red and yellow pigmented white concrete, while 7 percent dosage was needed for green pigmented white concrete. Overall, white cement results in better lively

shades and recommended over grey cement provided that other mechanical concrete properties are achieved.

- With the exception of green pigmented grey concrete, using a minimum dosage of 3 percent for pigmented grey and white concretes failed to mask cement and resulted in uneven faded color and thus it is not recommended for use.
- It is not recommended to use light pigments, yellow and buff as an example, for pigmenting grey concrete as they fail to mask the darker cement color using the maximum permissible dosage of 10 percent.

Similar to other research works and investigations, this work has limitations that includes the following:

- The lack of feasible, locally produced high quality pigments in the Egyptian market in addition to laboratory production which limits the scale of the specimen in this study.
- Absence of a spectrophotometer for further color assessment.
- The work has relied on three specific types of pigments. Thus, other pigment types or dosage may render different results.
- Further tests need to be conducted and expanded, particularly those related to concrete long term durability properties.
- The current inconsistencies coupled with the manufacturing process of locally produced white cement that negatively affected the experimental work and resulted in the variance between white and pigmented white concrete results.

5.2 Recommendations for Future Work

Pigmented concrete is a versatile architectural material that does not require an advanced construction technique but rather a careful and knowledgeable applicator. Nevertheless, several questions remain unanswered, thus the following recommendations can be stated:

- Introducing water reducing admixtures, super plasticizers and mineral admixtures aiming at enhancing the mechanical properties of pigmented concrete.
- Studying the validity of results herein for different types of coarse aggregates, types of chemical admixtures used and other concrete constituents.
- Studying the mechanical properties and color performance of pigmented concrete using other types of pigments, carbon black and cobalt blue for instance.
- Assessment of color performance of light colored pigments when added to grey cement using titanium dioxide.
- Pigment assessment using different pigments with white fine aggregates and investigating pigmented concrete solar reflectance properties.
- Further investigation for using color assessment technique on larger specimen scale and correlating results with chromatic readings of spectrophotometer.
- Investigating corrosion and fire resistance characteristics of pigmented concrete as well as abrasion resistance and weathering resistance properties.
- Performing long term hardened concrete testing including drying shrinkage, creep and chemical durability tests as better means of understanding the behavior and performance of pigmented concrete.

- Performing color assessment technique to address other issues regarding concrete surface and constituents. For instance, assessment of cement content in concrete as well as concrete subjected to fire.

5.3 Recommendations for Applicators

- Pigmented concrete is a state of the art architectural product that needs to be considered by designers and construction professionals as a potential addition to the increasing demand on environmentally sustainable and aesthetically satisfying materials.
- A detailed cost analysis needs to be performed to explore economic feasibility of pigmented concrete.
- Introducing automated dispensing system of liquid pigments for batching plants to maximize concrete consistency, repeatability, ease of use and cost effectiveness.
- Pilot experiments can be carried out for precast concrete plants to investigate the advantages of pigmented concrete mass production.
- Detailed specifications and mock-ups need to be provided prior to full implementation ensure that pigmented concrete complies with requirements of mechanical properties and final surface finish, texture and color.

In general, Table 5.1 present a summery for the behavior of the tested mixtures through a grey scale scheme. The scheme reflects mechanical performance, chloride ion penetration and color stability.

Table 5.1 Summary Conclusions for Mixtures' Performance

Mix ID	Mechanical Properties	RCPT	Dosage Saturation Point	Color Stability and Appeal
RG3	High	Moderate	None	Moderate
RG7	Good	High	High	Good
RG10	High	High	High	Good
RW3	Moderate	High	None	Moderate
RW5	Moderate	Good	High	High
RW7	Moderate	Fair	None	High
YG3	Good	Moderate	None	Fair
YG7	Good	Moderate	None	Fair
YG10	High	Good	None	Moderate
YW3	Good	High	None	Moderate
YW5	Moderate	Fair	High	High
YW7	Fair	Fair	None	High
GG3	Good	High	None	Good
GG5	High	Good	High	Good
GG7	Good	Good	None	Good
GW3	Moderate	Good	None	Moderate
GW5	Moderate	Good	None	High
GW7	Moderate	High	High	High

None	Fair Performance	Moderate Performance	Good Performance	High Performance

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Appendices

APPENDIX A

COLORIMETRY AND PHOTOGRAPHY GLOSSARY

16-bit: Image files that contain 65,500 different tones of information per channel. Photoshop CS5 can work with 8, 16 and 32-bit channels to provide more accurate colors.

Calibration: A process used to correct for the difference in output on a monitor, printer or scanner when compared to the original image. Calibration is never perfect but once done, the images you see on screen should represent closer similarity to printer output.

Camera Raw: A plug-in included with Photoshop CS that can correct or manipulate unprocessed images captured with digital cameras.

Center-weighed meter: A light measuring device that renders the middle area of the frame when calculating the correct exposure of an image.

Chroma: Color or hue.

CIE (Commission Internationale de l'Eclairage): Also known as the International Commission on Illumination, is a scientific organization working on matters related to color and lighting.

Colorimetry: The science that aims at specifying and reproducing colors as a result of measurement.

Compression: Reducing a file size by using fewer bits of information for encoding the original image. JPEG is a compression coding that discard some of the image information while TIF preserves all original details and discards only redundant data.

Crop: Trimming an image by adjusting or cutting-off its boundaries.

Diffuser: A built-in flash filter that softens image detail by randomly distributing grey tones resulting in a fuzzy effect.

Exposure: The amount of light allowed to reach camera sensor determined by the intensity of light. Also the amount admitted by the iris of the lens and the length of time determined by the shutter speed.

Eyedropper: A Photoshop CS image editing tool that can sample color from any part of an image or to obtain color information.

Fill lighting: Lighting that is used to illuminate shadows in photography. This can be done using electronic flash, reflectors or additional incandescent lighting.

Focal length: The distance between the camera sensor and the optical center of the lens when its focused on infinity. It is measured in millimeters.

Focus: Adjusting the lens to produce sharp image.

F/stop: The relative size of the lens aperture that determines exposure.

Gamut: The range of viewable and printable colors for a particular color space, for example RGB for monitors and CMYK for printing devices.

Greyscale: An image representation using 256 shades of grey.

Histogram: A chart showing the relationship of tones within an image using a series of vertical bars for each brightness level. It shows slopes and peaks depending on highlights, mid-tones and shadow tones present within an image.

Hue: The color of light that is reflected from an opaque object or transmitted through a transparent one.

Interchangeable lens: Lens designed to attached or detached from a camera.

(ISO) International Organization for Standardization: The organization providing standards used for light sensitivity of digital cameras' sensors. The camera's sensitivity is expressed in "ISO" settings.

JPEG: Or Joint Photographic Experts Group, is a file format that supports 24-bit color and reduces file size by selective discarding of image data.

Kelvin (K): A unit of measurement based on absolute temperature scale and is used to describe the color of continuous spectrum light sources.

Lens aperture: The lens opening that admits light to the sensor. Aperture size is measured in f/stops were f/2 aperture is larger than f/16 as an example.

Luminance: Human eye does not see light, but the light reflected from an object which is called luminance. Color luminance is a measure to describe the perceived brightness of a color.

Neutral color: In RGB color space, a color with equal red, blue and green producing grey.

Primary Colors: The red, green and blue hues which are used separately or in combinations to create all other colors captured with a digital camera or produced and edited on computer monitor.

Pixels per inch (ppi): The number of pixels that can be displayed per inch from a scanned image or on a monitor.

RAW: An image file format that includes unprocessed information captured by digital camera. RAW files contain huge color information that needs to be rounded up or corrected by special softwares.

Saturation: The purity of color or the amount by which a pure color is diluted with white or grey.

Single Lens Reflex (SLR) camera: A camera that allows to see through the lens using the camera's viewfinder. The viewfinder sees the same image as the camera sensor. Other functions like light metering and flash control also operate through the lens.

Tint: A color with white added to it. Often referred to the percentage of one color added to another.

TTL: A system that provides calculation of exposure, flash exposure or focus based on the view through the lens.

Visible light: Electromagnetic radiation visible to human eye at wavelengths of 400-700 nm.

White Balance: The adjustment of a digital camera to the color temperature of the light source.

APPENDIX B

DIGITAL IMAGES CAPTURED AT 7, 28 AND 56 DAYS