Making of Strong and Durable Concrete

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The most two important properties of hardened concrete are its compressive strength and durability. This paper presents the results of a wide range of experiments which show how high strength, which benefits durability, was achieved through the use of adequately graded aggregates, optimal maximum nominal size, shape and type of coarse aggregate, application of low water/cement ratios encouraged by use of locally-developed plasticizers, preparation of mixes free from clayey particles and organic matter, and the use of progressive curing methods. The paper also reveals how concrete durability could be enhanced through the use of optimal amount of cement, employment of Portland-pozzolana and low-heat Portland cements and adequate compaction, which makes for impermeable and watertight concrete. The work further shows that in circumstances where concrete structures are liable to freezing and thawing, concrete durability can be further enhanced through uniform entrainment of air bubbles of optimal dimensions and total volume.

Keywords: aggregate’s size and shape, air – entrainment, concrete strength, durability.

1. INTRODUCTION

Concrete is a heterogeneous material obtained by mixing cement paste (binder) with aggregates (filler), the later constituting more than 80% of the concrete, Blackledge[1]. The binder (cement and water) glues the filler (fine or coarse aggregate, or both) together to form a synthetic conglomerate.

Sometimes material other than water, aggregates and hydraulic cement is added to concrete batch before or during mixing, to provide a more economical solution and enhanced concrete properties. Such a material is known as admixture. It is difficult to imagine the modern society without concrete. It finds wide application in buildings, roads, bridges and dams, among others.

The most two important properties of hardened concrete are its compressive strength and durability. The former can be quantitatively measured while the latter cannot. Notwithstanding some possible exceptions such as the thickness of concrete cover, it can be said that generally, factors that favour concrete strength usually benefit its durability. Factors that affect the strength and durability of concrete include quality and quantity of cement used in a mix, grading of aggregates, maximum nominal size, shape and surface texture of aggregate, Arum and Alhassan[2] water/cement ratios, curing method, Aluko[3] presence or otherwise of clayey particles and organic matter in the mix, Arum and Udoh[4].

Other factors affecting concrete strength and durability include the use of admixtures, employment of Portland-pozzolana and low-heat Portland cement, as well as the level of concrete compaction.

In this paper, it will be shown how the various constituents of cement partake in the hydration process with water and how this process affects the strength of concrete. This chemistry will help among other things to explain why the strength of concrete increases with age. Literature will be reviewed to ascertain how all those factors listed above affect the strength and durability of concrete. Finally, some progressive trends for future development of strong and durable concrete will be highlighted.
2. CEMENT, WATER, AND THE HYDRATION PROCESS

Cement is a mixture of compounds made by burning limestone and clay together at very high temperatures ranging from 1400 to 1600°C. In this work the term cement refers to Portland cement. Portland cement consists of five major compounds and a few minor compounds. The composition of a typical Portland cement is given by weight percentage in Table 1.

<table>
<thead>
<tr>
<th>Cement Compound</th>
<th>Weight Percentage</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate</td>
<td>50</td>
<td>Ca₃SiO₅ or 3CaO·SiO₂</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>25</td>
<td>Ca₂SiO₄ or 2CaO·SiO₂</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>10</td>
<td>Ca₃Al₂O₆ or 3CaO·Al₂O₃</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>10</td>
<td>Ca₄Al₂Fe₂O₈ or 4CaO·Al₂O₃·Fe₂O₃</td>
</tr>
<tr>
<td>Gypsum</td>
<td>5</td>
<td>CaSO₄·2H₂O</td>
</tr>
</tbody>
</table>

Source: Bye [5]

When water is mixed with cement, it forms a paste that binds the aggregate together, causing the hardening of concrete through a process called hydration. Hydration is a chemical reaction in which the major compounds in cement form chemical bonds with water molecules and become hydrates or hydration products. Tricalcium silicate is responsible for most of the early strength (first 7 days). Dicalcium silicate reacts more slowly and so contributes only to the strength at later ages. According to Bye [5], the equation for the hydration of tricalcium silicate is given by:

Tricalcium silicate + Water → Calcium silicate hydrate + Calcium hydroxide + heat  
2Ca₃SiO₅ + 7H₂O → 3CaO·2SiO₂·4H₂O + 3Ca(OH)₂ + 173.6 kJ

Upon the addition of water, tricalcium silicate rapidly reacts to release calcium ions, hydroxide ions, and a large amount of heat. The pH quickly raises to over 12 because of the release of alkaline hydroxide (OH⁻) ions. This initial hydrolysis slows down quickly after it starts, resulting in a decrease in heat evolved. The reaction slowly continues, producing calcium and hydroxide ions until the system becomes saturated. As soon as this occurs, crystallization of the calcium hydroxide commences. Side by side with this, calcium silicate hydrate begins to form. Ions precipitate out of solution, accelerating the reaction of tricalcium silicate to calcium and hydroxide ions. The evolution of heat is then greatly increased.

The calcium silicate hydrate crystals grow thicker, making it more difficult for water molecules to reach the unhydrated tricalcium silicate. The speed of the reaction is now controlled by the rate at which water molecules diffuse through the calcium silicate hydrate coating. This coating thickens over time causing the production of calcium silicate hydrate to become slower and slower.

Dicalcium silicate also affects the strength of concrete through its hydration. Dicalcium silicate reacts with water in a similar manner as for tricalcium silicate, but much more slowly. The heat released is less than that by the hydration of tricalcium silicate because the Dicalcium silicate is much less reactive. The products from the hydration of dicalcium silicate are the same as those for tricalcium silicate:

Dicalcium silicate + Water →  
2Ca₂SiO₄ + 5H₂O  
Calcium silicate hydrate + Calcium hydroxide + heat  
3CaO·2SiO₂·4H₂O + Ca(OH)₂ + 58.6kJ

The other major components of Portland cement: tricalcium aluminate and tetracalcium aluminoferrite; also react with water. Their hydration involves reactions with the gypsum as well. However, because these reactions do not contribute significantly to strength, they are not shown here.

3. WATER / CEMENT RATIO AND THE STRENGTH OF CONCRETE

The strength of concrete depends very much upon the hydration reaction discussed above. Indeed, water/cement ratio of concrete is the single most important factor that influences the strength of concrete [1,7,17]. The strength of concrete increases when less water is used to make concrete. The hydration reaction consumes a specific amount of water. Concrete is usually mixed with more water than needed for hydration. The extra water is needed to give concrete sufficient workability. Flowing concrete is desired to achieve proper filling and composition of the moulds. The water not consumed in the hydration reaction will remain in the microstructure pore space. These pores make the concrete weaker due to the lack of strength-forming calcium silicate hydrate bonds. Porosity is thus determined by the water to cement ratio. Low water to cement ratio leads to high strength but low workability. High water to cement ratio leads to low strength, but high workability.

4. EFFECT OF AGGREGATE’S SIZE, SHAPE AND TEXTURE ON THE STRENGTH OF CONCRETE

4.1. Size of Aggregate

The physical characteristics of aggregate are size, shape and surface texture. These can indirectly affect strength because they affect the workability of the concrete. If the aggregate makes the concrete unworkable, more water is added and this weakens the concrete by increasing the water to cement ratio.

Kong and Evans [8] assert that as the nominal maximum size of the aggregate increases, a lower water to cement ratio can be used for a given
workability, and a higher strength is obtained. However, they maintain that the foregoing assertion applies for a nominal maximum size of aggregate up to 40mm, above which the gain in strength due to the reduced water/cement ratio is offset by the adverse effects of the lower bond area between the cement paste and the aggregate, and of the discontinuities caused by the large particles. It is also important to ensure that for reinforced concrete the nominal maximum size of aggregate should be such that the concrete can be placed without difficulty, surrounding all reinforcement thoroughly and filling the corners of the formwork, Barnbrook et al [7].

In a research done by Raheem and Aderounmu [8] on the effect of size of aggregate on the strength of concrete, they concluded that the compressive strength of concrete increases with increase in the size of coarse aggregate up to a maximum of 25mm, beyond which strength of concrete begins to decrease.

4.2. Shape of Aggregate

The particle shapes affect the strength of concrete mainly by affecting the cement paste content required for a given workability. If the cement content is the same, then an angular aggregate would require a higher water/cement ratio than an irregular one, which in turn will require a higher water/cement ratio than a rounded one, Kong and Evans [6]. According to Neville [9] and Kaplan [10], the effects of particle shape tend to be beneficial to strength where the predominant particle shape is generally equi-dimensional and detrimental where it is flaky and/or elongated.

Flakiness of coarse aggregate has an adverse influence on the workability and mobility of concrete. Flakiness in fine aggregates also affects the properties of the concrete mix. This can lead to problem of bleeding and segregation in the fresh mix leading to reduced strength and durability of the resulting hardened concrete.

4.3. Surface Texture of Aggregate

Surface texture affects concrete in two ways. Firstly, it affects the bond between the cement paste and the aggregate particles. Secondly, it affects the cement paste content required to achieve a given workability. On balance, a rough surface results in a higher concrete strength.

5. EFFECT OF AGGREGATE’S GRADING ON THE STRENGTH OF CONCRETE

The proportions or amounts of the various sizes of particle making up the aggregate are found by sieving and the result is known as grading. The grading is usually given in terms of the percentage by weight passing the various sieves. If the amounts of the various sizes differ from batch to batch of the concrete mixes, the workability and the strength of the concrete will also vary from batch to batch. A graded coarse aggregate is one, which is made up of stones of different sizes, ranging from large to small.

For concrete to be durable it has to be dense and, when fresh, it should be sufficiently workable to be properly compacted. The mortar should be slightly more than sufficient to fill the voids in the coarse aggregate; in turn the cement paste should be slightly more than sufficient to fill the voids on fine aggregate. The voids on an aggregate depend on its grading.

The grading of the aggregates affects the strength of concrete mainly indirectly, through its important effect on the water/cement ratio required for a specified workability, Kong and Evans [6]. A badly graded aggregate requires a higher water/cement ratio and results in a weaker concrete.

6. EFFECT OF ADMIXTURES ON THE STRENGTH OF CONCRETE

An admixture is a material other than water, aggregates and hydraulic cement that is used as an ingredient in concrete or mortar and is added to the batch immediately before or during its mixing. Concrete’s strength may be affected by the addition of admixtures. Some admixtures add fluidity to concrete while requiring less water to be used. An example of admixture, which affects workability, is super plasticizer. This makes concrete more workable or fluid without adding excess water.

Admixtures can be generally grouped as follows:

Air-entraining agents: These are added primarily to improve freeze-thaw durability. They also improve workability and reduce bleeding. Examples include special detergents.

Retarders: These delay setting time, offer more long-term strength and offset adverse high temperature weather. Example is sugar.

Accelerators: These speed setting time, give more early strength, and offset adverse low temperature weather. Example is calcium chloride. Although calcium chloride speeds up the concrete setting time, the chloride ions destroy the passive film that protects steel bars from corrosion. This is a major disadvantage of using calcium chloride as an accelerating admixture.

Water-Reducing Admixture: These admixtures lower the water required to attain a given slump, thus lowering the water to cement ratio. This will in turn improve the strength, water-tightness and durability of concrete. In the alternative, they may also be used to maintain the same water/cement ratio but increase workability for difficult placement. Typical reductions in water requirements are 5-10%. The water reducers reduce the electronegative charges on the fine cement particles allowing them to disperse more readily in the water. This reduces the tendency for flocculation of the cement particles in the paste.

Super plasticizers: These are high-range water reducers, which can reduce water contents by 15-30%. They are linear polymers containing sulfonic acid groups attached to the polymer backbone at regular intervals. Super plasticizers give increased compressive strength due to ability to reduce water/cement ratio and better dispersion of cement in paste. They also increase durability due to lower water/cement ratio. They give rapid strength gain without increased heat generation and are used for high strength concrete. Commercial formulations include sulfonated melamine-formaldehyde condensate; and naphthalene sulfonate-formaldehyde condensate.

Mineral Admixtures: These are finely divided solids to improve workability, durability, strength, or provide additional cementing properties. Examples include slags, silica fume, fly ash, and pozzolana.

Miscellaneous Admixtures: These are the admixtures that don’t fall under the above categories. These include bonding admixtures, corrosion inhibitors, damp proofing admixtures, expansion-producing admixtures, grouting admixtures, pigments.

7. EFFECT OF CURING ON THE STRENGTH OF CONCRETE

After setting, concrete increases in strength with age. Suitable curing of the concrete whilst it is maturing can further increase the strength at a particular age. Curing can be affected by the application of heat and/or the preservation of moisture within the concrete. Curing by preventing the water used in mixing from escaping is usually done in one of the following ways, Wilby[11]:

a. flooding or submerging the concrete in water;
b. treating (for instance by painting) the surface of the concrete so that it cannot dry out; and
c. covering the concrete with damp sand or hessian fabrics, which are kept damp by watering periodically, or with thin polythene sheet.

8. EFFECT OF CLAYEY PARTICLES AND ORGANIC MATTER

For good quality concrete, dust or clayey matter should not be present in excessive quantities on the surfaces of the aggregate particles; otherwise the bond between the aggregate particles and the cement paste may be reduced[1,3,12]. In fact, according to British Standards[13], coarse aggregates should not contain clay, silt or fine dust in amounts more than 1% by weight while natural sands should not contain materials, which are likely to decompose or change in volume when exposed to the weather, or materials that will adversely affect the reinforcement. Such undesirable materials include coal, pyrite and lumps of clay, which may soften and form weak pockets.

9. DURABILITY OF CONCRETE

The durability of concrete is its ability to resist deterioration resulting from external and internal causes. The external causes include the effects of environmental and service conditions, such as weathering, chemical actions and wear. The internal causes are the effects of interaction between, the constituent materials, such as alkali-aggregate reaction, volume changes, absorption and permeability.

The main requirements for durability are (Institution of Structural Engineers[14]):

a. an upper limit to the water / cement ratio;
b. a lower limit to the cement content;
c. a lower limit to the concrete cover to reinforcement;
d. good compaction; and
e. adequate curing.

The upper limit to the water/cement ratio, the lower limit to the cement content and the lower limit to the concrete cover are all given in BSI 8110[15]. In addition to lower limit to the cement content, BSI 8110 specifies 550kg/m³ as the maximum cement content in recognition that high cement content increases the risk of cracking due to drying shrinkage in thin sections or to thermal stresses in thicker sections.

Ensuring full compaction can enhance durability, which contribute to producing a dense, impermeable concrete. Another factor, which enhances concrete durability, includes the use of Portland-pozzolana and low-heat Portland cements. Portland-pozzolana cement reduces heat of setting and thus reduces shrinkage without reducing the 28-day strength of the concrete. This is achieved by substituting fly ash (i.e. pozzolana) for 15-35% by mass of the ordinary Portland cement. Low heat Portland cements generate less heat upon reacting with water compared with other cements and are thus suitable for mass concrete work. In this way flash setting of the cement and voids in the resulting concretes, are avoided.

Another important factor that enhances durability of concrete subject to freeze-thaw environment is air entrainment. The mechanism by which air-entrainment enhances durability can be appreciated with the understanding of the air-void system as follows.

As unreacted water freezes it expands 9% by volume on phase change, Neville and Brooks[16]. This internal volume expansion causes internal stresses in the matrix. It can generate cracks in the concrete, which may allow water to infiltrate and the process can get progressively worse. It can lead to significant degradation of the concrete. The formation of ice in the pore spaces generates pressure on any remaining unfrozen water. Introducing a large quantity of air bubbles provides a place for this water to move in to relieve the internal pressure. It is more beneficial to generate very small air bubbles well distributed
throughout the matrix than a smaller number of larger bubbles. Total air content is only a part of the formula for frost resistance. The nature of the entrained air is equally important. The critical parameter of the air-entrained paste is the spacing factor, which is the maximum distance from any point in the paste to the edge of a void. It should not exceed 0.2mm. The smaller the spacing factor the more durable the concrete. The air bubbles themselves should be in the range of 0.05-1.25mm in diameter.

10. RESULTS OF RECENT RESEARCH ON IMPROVEMENT OF STRENGTH AND DURABILITY OF CONCRETE

Arum and Udoh [4], Arum and Alhassan [2], and Aluko [3] carried out a wide range of laboratory experiments recently aimed at improving the strength and durability of concrete. The main conclusions from these experiments are now presented:

10.1. Effect of Dust Inclusion in Aggregates on the Strength of Concrete

Arum and Udoh [4] showed the following:

- Presence of dust (silt and clay) in aggregates can reduce the compressive strength of concrete by as much as 52% at 30% content and as much as 57% at 52% content. This result shows that significant increase in dust content has minimal impact on the percentage reduction of concrete compressive strength. To explain this behaviour, it is pertinent to note that dust decreases the strength of concrete by two mechanisms: by reducing the bond between cement paste and aggregate, and by increasing the water requirement of the concrete which results in increased water to cement ratio. However as the dust content of the concrete rises to some certain level, the reduction in bond strength decreases. In addition, although water requirement continues to rise as dust content increases, it is known, Kong and Evans [6] that as water/cement ratio increases to about 0.7, strength of concrete rapidly decreases but as this ratio increases beyond 0.7, the strength of concrete begins to decrease more gradually.

- The magnitude of reduction in the strength of concrete with increase in dust content depends on the type of coarse aggregate used.

10.2. Effect of Shape Texture and Size of Aggregate on the Strength of Concrete

In their work, Arum and Alhassan [2] produced two major classes of concrete, each consisting of 4 sub classes. Class 1 consisted of coarse aggregates in the form of crushed angular granite with rough surface texture while class 2 consisted of coarse aggregates in the form of water-worn rounded pebbles with smooth surface texture. Each subclass in a major class differed from the others by the nominal maximum size of its coarse aggregate, which was either 20mm, 25mm, 30mm, or 37.5mm. In all 48 standard concrete test cubes (150x150x150mm) were cast, 6 for each subclass. 3 cubes each were crushed at maturity ages of 7 and 28 days. For the assessment of the workability of concrete, a standard slump cone was used. Starting with a water/cement ratio of 0.4, water was intermittently added until a workable mix was obtained for each concrete subclass. The results of this work showed that:

a. the compressive strengths of concrete with rough angular granite are higher than those of concrete with smooth water-worn rounded pebbles;

b. for a given workability, concrete made from smooth water-worn rounded gravel aggregate requires a lower water/cement ratio than concrete made from rough angular granite;

c. the gain in strength due to improved bond characteristics is greater than the gain in strength due to reduced water/cement ratio; and

d. the compressive strength of concrete increases as maximum nominal size of aggregate increases up till 25mm above which its behaviour tends to depend more on the surface texture, and the shape of aggregate.

10.3. Comparative Assessment of Concrete Curing Methods

Aluko [3] compared five methods of laboratory concrete cubes curing. These methods include:

a. curing by immersing concrete in water;

b. curing by covering concrete with polythene membrane;

c. curing by spraying water on concrete periodically;

d. curing by covering concrete with wet sand layer; and

e. curing by covering concrete with wet hessian fabric.

This comparison showed that concrete cube specimens cured by periodic spray of water had the greatest strength gain over time. From this result it seems appropriate to conclude that this method of curing provides the optimal amount of water for the continuation of hydration of cement in concrete without any excess water that will merely increase the water/cement ratio and lead to decrease in strength.

11. DEVELOPMENT OF STRONG AND DURABLE CONCRETE

Many research activities are going on in Nigeria at present on ways of improving the quality of concrete. Two of such research efforts deserve a mention here. One is on the development of a bio-based concrete accelerating admixture as an alternative to calcium chloride. The other is on the development of a bio-based concrete retarding admixture for tropical environments.
11.1. Development of Bio-based Accelerating Admixture

At present, two groups of accelerators are known namely soluble organic compounds (such as triethanolamine, calcium formate, calcium acetate) and soluble inorganic compounds (such as calcium chloride, sodium chloride, carbonates, silicates, fluorides, fluosilicates, ferric salts). Among all these accelerators, calcium chloride is the most widely used because it is the most economical and most effective accelerator. The advantages of this accelerator include increasing the workability of fresh concrete, reducing the water required to produce a given slump, reducing concrete bleeding, and reducing the initial and final setting times of concrete.

However, calcium chloride possesses several disadvantages, which include reducing the resistance of cement to sulphate attack, promoting corrosion activity of the steel reinforcement and increasing the drying shrinkage and creep of concrete usually by about 10% to 15% (10). The corrosion related problem of calcium chloride has led to its limited use and outright ban in some countries. Other compounds have been investigated to determine their efficacy as accelerators but none of them has been able to achieve the same level of efficiency as calcium chloride. In addition, these other compounds are much more expensive than calcium chloride.

Test results show that some locally available leaves contain organic compounds such as acetates and formates of calcium (among several others) which have been individually researched and successfully used to accelerate the setting time and rate of strength gain of concrete without the attendant drying shrinkage and heightened creep experienced with the use of calcium chloride. In addition, calcium chloride causes flash set of concrete because it rapidly accelerates the rate of hydration of the calcium silicates in cement by reducing the alkalinity of the mix while generating a lot of heat, leading to reduced durability on the long run. The preliminary results indicate that the alternative accelerator under research will be able to accelerate the hydration of cement at low temperatures while increasing the early strength of concrete and either improving or maintaining the strength in the long run. Also since this alternative will be chloride free, the risk of corrosion to the reinforcing steel in the concrete will be eliminated. Work on this admixture is on-going at present.

11.2 Development of Bio-based Retarder

A liquid contained in abundance in a locally available (in Nigeria) tree species has been identified. This liquid contains some complex sugars and their derivatives. Test results show that used in calculated dosages in concrete; it offsets the effects of high temperature by increasing setting time. Like other known commercially available retarders, it slows the rate of early hydration of tricalcium silicate by extending the length of the dormant period and also appears to retard the hydration of tricalcium aluminate. It was also noted that a delay in the introduction of this liquid until the concrete has been mixed tended to enhance its performance.

In addition to delaying the set of the concrete, it increases slump at the same water / cement ratio and enhances strength gain through reduction of water requirement for a given mix. Surely this readily available and relatively low-cost potential concrete retarding bio-based admixture has a future. Work on this potential retarder is on-going to harmonise various experimental results on workability, setting time and strength of concrete made with the addition of this liquid.

12. CONCLUSION

This paper has highlighted the various ways in which the strength, durability and the general quality of concrete can be improved through the use of well graded aggregates, low water/cement ratios, effective curing methods, clean aggregates, optimal maximum nominal size, shape and surface texture of aggregates. Presented also were the beneficial effects of uniform entrainment of air bubbles of optimal dimensions and amount, use of Portland-pozzolana and low-heat Portland cements. It was also shown that research works are actively proceeding on the development of bio-based low-cost concrete accelerators and retarders for the future.

REFERENCES


