NEVER MIND THE QUALITY - CRUSH THE CUBE!

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ABSTRACT

Ever since its invention in the mid 1860’s by Grant of the Metropolitan Water Board in London, UK, the concrete cube test has been used as a means to specify & assess the strength of concrete used for construction purposes. Although it is important to produce concrete of an acceptable strength in order to insure the structural stability of a building or structure it is not the only important property of the concrete to be considered. Many young engineers tend to be obsessed with concrete strength & pay scant attention to other important properties such as the long-term durability & surface appearance of the concrete. Provided, when the cube is crushed, the result is in excess of some magic number, the result can be neatly filed & forgotten. But is it as simple as that? & what action needs to be taken if for some reason the cube strength does not live up to its expectations. What does the cube strength result really mean, & is the insitu strength reflected in that attained by the cube? If we decide to check the insitu strength of the concrete by cutting concrete cores or doing some form of non-destructive test what does that tell us about the concrete & are the results any more reliable. If the strength of the concrete is high does it mean that the long term durability & surface appearance will be enhanced or are other aspects of the concrete materials technology almost equally as important as the strength?

Introduction

The concept of the strength of concrete seems to have originated at the Great Exhibition held in the Giant Crystal Palace, built in London’s Hyde Park & opened in 1851. Here many of the great industrial developments of the Victorian Industrial Revolution were first brought to the attention of the general public. Fox Talbot was demonstrating his invention of photography & several cement makers were anxious to demonstrate the enhanced qualities of Portland Cement. In order to demonstrate the superiority of their product they cast it into large blocks & then cut cubes out of the blocks & tested them in compression in hydraulic presses. They were able to demonstrate the advantages of the relatively recently developed product over that of the more traditional lime concrete. However it was more than ten years later that the idea of assessing the strength of concrete was put forward by Grant using the technique of casting the concrete into cube moulds, storing the cubes in water & then crushing them. Initially cubes were crushed at 1,3,5,& 7 days. At these ages it was already possible to see the advantages of early strength gain over the traditional lime concretes. But in those days cement was only coarsely ground & so it continued to gain in strength well after 7days. The early gain in the strength is a function of both the Tricalcium Silicate & the Dicalcium Silicate in the cement. The higher the temperature at which the cement is fired during its production, the higher is the percentage of Tricalcium Silicate that is formed. The Tricalcium Silicate influences the early strength gain & the Dicalcium Silicate influences the gain in strength at later ages. Early Portland cements were fired in bottle kilns & the temperature of firing was not much better than that of traditional lime production. It was not until Isaac Johnson improved the firing process & later when Ransome developed the Rotary Kiln that significant improvements were made in cement strength gain characteristics. Anyway Grant discovered that he obtained more consistent results when he tested the concrete after a period of 28days from the time of adding the mixing water & casting the concrete. Hence the 28day concrete cube test evolved.
Strength assessment
There is nothing magic in 28 days. It is important to realise the reason why the 28day test was invented & that contrary to popular belief concrete does NOT normally stop gaining in strength at 28 days. This fact is extremely important in exercising engineering judgement in deciding what action to take in the unfortunate situation when the strength of concrete fails to live up to its anticipated expectations at 28 days.

What the numerical value of strength, usually expressed in MPa or N/mm² (or in lb/in² if you are an American still living in the 20th Century) really means is discussed later in the paper. Sufficient to say that implementation of strength specifications causes much confusion on construction sites. Figure 1 is a good example of the implementation of a concrete strength specification. When the concrete in this wall was sampled & cast into cubes, at the time of test one cube fell 0.5MPa below the specified minimum strength requirement. When this happens the specification calls for 3no 100mm diameter concrete cores to be cut from the structure & tested. One of the cores was 0.5MPa below the required estimated cube strength. In this situation the specification calls for a further nine cores to be extracted & tested. All nine cores complied with the strength specification & so the holes in the concrete (which resembled a piece of cheese) were filled in & the wall was accepted!

However this is a stupid implementation of a strength specification & is just based on numbers rather than sensible engineering judgement. The concrete should never have been accepted. Too much water was added to the concrete & it suffered from severe plastic settlement cracking as a result. The cracks were so wide it was possible to see right through the wall. This was enough to condemn the concrete in the first instance, especially since it was near the sea & subject to chloride attack. Also the high water content of the concrete had made it extremely permeable & therefore highly absorbent. But the strength complied & so the wall was accepted.

In many instances concrete is specified to be too strong, in theory to ensure high durability requirements. Two years ago I was asked to investigate a well known Singapore project where precast concrete elements were condemned because the specified strength was set at 70MPa but the units only achieved 65MPa. Actually, in engineering terms the concrete only needed to attain a strength of about 40MPa. However it was thought that the extra 30MPa would enhance the durability. In spite of my efforts over 800 perfectly usable, fairly large precast elements were condemned as scrap due to a poor grasp of concrete materials technology & an arrogant opinion by the engineer.

So when we crush a cube & obtain a result of, say, 40MPa what does that result really mean? That the concrete in the structure has a strength of 40MPa? Certainly not. To start with the cube test is a means of assessing the production quality of the concrete; that is its potential strength, not its actual strength. This point also often leads to considerable confusion on site. Used on a like for like basis it is a good indicator of the production quality of the concrete.

Does a test result really indicate that the cube strength is 40MPa? Many things affect the indicated cube strength. It is easy to demonstrate this by testing a wet cube & a dry cube. The dry cube will produce the higher result. This is because the dry cube surface exerts a greater coefficient of friction between the concrete surface & the testing platten of the crushing machine. Also the pore water pressure inside the wet cube will influence the result as the cube deforms under load. If the cube has mould oil on its surface, the coefficient of friction will also be lowered, between the platten & the cube, resulting in a lower test result.

Also the rate at which the load is applied to the cube influences the result. Generally the cube result will be higher at a faster rate of loading. This is because at lower rates of loading the concrete can be affected by the influence of creep under load resulting in a redistribution of stress within the specimen.

These points are obvious, & it could be argued that if the cube is tested strictly in accordance with the relevant standard such variations in indicated strength can be avoided. However the cube strength is also influenced by the degree of compaction & the curing temperature, & whether the curing process starts as soon as the compaction of the cube is completed. Cubes are seldom properly cured on site & this also has a major influence on the measured cube strength.

Another aspect of cube testing that is often overlooked is the stability of the compression testing machine.
When a cube is made it is not of uniform strength throughout the specimen. This is because the concrete in the bottom of the mould tends to be more thoroughly compacted & also after the cube is cast, bleed water tends to migrate towards the top surface as happens in the concrete structure itself. Therefore the top of the cube is always slightly weaker than the bottom section. Cubes are placed in the machine not in the as cast position but on their sides. The top platen of a testing machine aligns itself on the cube surface with a hemispherical ball seating which is supposed to lock under load once it has aligned with the cube surface.

However, in Asia the high ambient humidity tends to cause the hemispherical surfaces to rust. People then tend to put oil or WD40 on the surfaces. This causes the platen to slip under load usually causing premature failure of the top section of the cube. This type of failure is easy to detect from an examination of the failed test specimen. But the slippage problem of the ball seating may have to be considerably advanced before the problem is noticed by examining the cube. The rigidity of the machine can be checked using an electronic frame stability tester, known as a Footemeter after its inventor Peter Foe. Other methods include placing an aluminium cube in the machine with Polaroid disks on each vertical face. Differential deflection can be observed from changes in the pattern on the Polaroid disk.

Even if the load indication of a testing machine is checked with a load column or a pressure transducer the machine can still give inaccurate results because of tilting of the top platen under load due to the ball seating does not lock in position effectively whilst loading of the cube. Before its demise the UK Cement & Concrete Association used to offer a Reference Testing Service for cube testing machines. The service involved the production of very low variability concrete cubes. Twelve cubes were made of a particular strength. Six were tested on the Association's very accurate reference testing machine & six were sent to the client to be tested on his machine at the same time. This helped to pick up errors that normal load columns were not capable of detecting. Sadly after the closure of the C&CA this service was not continued by any other organisation.

It is also very essential to position the specimen directly in the centre of the axis of the applied load. Errors of fraction of a millimetre can seriously influence the result.

When a cube is tested the specimen has a height/cross section ratio of 1. Where cylinders are tested in compression in accordance with the ASTM standards they have a height diameter ratio of 2. The effects of what Structural Engineers refer to as Slenderness Ratio come into play & therefore a cylinder will always give a lower compressive strength for the same concrete.

For this reason when research into concrete core testing was carried out by the Concrete Society of UK & published in its Technical Report CSTR 11, they proposed the specimens also should have a height /diameter ratio of 1. Another important aspect of this report was to draw attention to & emphasise the difference between potential strength, as measured by the concrete cube result, & actual strength measured by taking cores from the insitu concrete. It also drew attention to differences in concrete strength between for example the bottom & top of a wall. This point was also later emphasised by Henry Tomsett in his advisory note on the interpretation of Ultrasonic Pulse Velocity results. The report also highlighted differences between cores cut vertically & horizontally from a structure. These include the problem of under-aggregate fissures due to the presence of bleed water in the mix.

Testing the compressive strength of concrete is relative. No one knows what the exact compressive strength of concrete really is because different testing methods or specimen sizes will produce different results. All we can say is that the strength of the cube is probably somewhere within the region of the indicated strength.

**Insitu strength**

There has been much research into other methods of assessment of strength, especially the insitu strength. However in order to assess the strength, most of these test methods measure some other property of concrete which is only indirectly related to the compressive strength.

Probably the best known so called non-destructive test is the Rebound Hammer, which measures the rebound characteristics of a concrete surface. It is useful for comparing similar concretes on a like for like basis, but the graph of rebound number against strength supplied with the instrument is that of a
Swiss limestone aggregate concrete of 1947 vintage, which may bear very little resemblance to the concrete under test. The instrument is however useful in assessing the abrasion characteristics of concrete surfaces. Where a rebound hammer is carefully calibrated against concrete of a known strength, estimates of the strength of other concretes cast against the same type of mould surface & with similar curing regimes can be fairly accurate. Sadly the Rebound Hammer has, over the years, been sadly abused as a test by the Ready Mixed Concrete Industry where it is often used to demonstrate that even hopelessly weak concrete complies with the specification. However when in the right hands it is a very useful quality control tool.

Ultrasonic pulse velocity testing is another popular test used for insitu strength testing. This relates the speed of sound passing through concrete to its strength. The speed of sound is actually related to the modulus of elasticity & Poisson’s Ratio of the concrete which are only indirectly related to strength. Again this test is useful in testing concrete by comparison with concrete of known strength, on a like-for-like basis. The measured velocity is also influenced by the aggregate volume concentration of a particular mix.

Strength is not the only property of concrete that is important. The performance of concrete depends on other factors apart from strength. One of the most important is the permeability of the concrete. It cannot be over emphasised that the long term durability of concrete & its surface appearance depends on the waterproof qualities of the original mix. Contrary to all the high-pressure sales talk by suppliers of materials aimed at densifying the concrete matrix, absolutely NO plain concrete is waterproof without the inclusion of an integral waterproofer in the mix at the production stage. Many types of chemical additions claim to be capable of waterproofing concrete but stearate based chemicals tend to offer the best long term performance. The addition of a waterproofing admixture represents a minute cost of the concrete production process & should always be considered where long term durability is important. The cost of repairing concrete that has not been waterproofed can be upto 400 times the cost of the inclusion of a waterproofer in the first instance & therefore represents both sound technical & commercial sense.

Producing smooth uniform coloured grey concrete is almost an impossibility because even very slight changes in the batch proportions, formwork absorbency, or compaction processes can have a marked effect on the surface appearance of the hardened concrete. For that reason plain flat concrete surfaces are never likely to succeed & should never be specified unless they are to be painted. Textured, profiled or exposed aggregate surfaces are more suitable where the finish of the concrete is important. The finish of high strength concrete can be good but other aspects are also essential to consider. Uniformity & a high level of quality control are of paramount importance. These aspects are almost equally as important as obtaining the correct strength. For example two concrete mixes of the same strength can differ widely in appearance & quality just on the batch proportions alone. Much emphasis is now being placed on uniformity & optimising of the combined aggregate grading as well as nanotechnology of the concrete microstructure.

Today’s concretes are becoming highly sophisticated but site production still lags far behind in its ability to exploit the new technological advances that are taking place in modern concrete materials technology.

So that although strength is important other parameters of the concrete such as appearance & long term durability need to form an integral aspect of any specification. Also it is important to exercise sensible engineering judgement in regard to implementing strength compliance aspects of concrete. It is a nonsense to condemn concrete that is 0.5MPa below a specified value. The result is also influenced by sampling & testing errors. In addition what strength is really necessary in order to ensure the structural integrity, stability & durability of the concrete. These are areas to which scant attention has really been paid & future research is absolutely necessary. With the advent of rapid high-rise construction the relationship between the elastic strain, creep strain & long term drying shrinkage also need further investigation. Rapidly constructed buildings shorten by an alarming rate of upto 1.4mm/metre in Asia over a 15 year period & this is of course directly related to the initial strength & total water content of the concrete mix, combined with the age of loading & also relative humidity & environmental conditions.

Therefore strength is important but so are other aspects of concrete materials technology which are often overlooked in the quest for that magic cube crushing strength result.
Plate 1
Concrete wall showing an excessive number of cores extracted as a check because one cube was 0.5N/mm² below the target strength.

Plate 2
An unusual collapse of a building because the concrete was below the specified strength.
Plate 3
Concrete cantilever which surprisingly did not collapse even though there is no steel reinforcement in the lower section of the wall in an area of critical stress.

Plate 4
Plain uniform colour concrete is almost impossible to achieve and will never succeed unless it is painted.
Plate 5
Concrete wall stained due to the incorrect application of concrete mould release agent onto the formwork.

Plate 6
Relationship between the strength of cubes, cores and in-situ strength of concrete in the structure.
Plate 7
Problem that develops when a concrete cube is inserted in a testing machine on its side & the ball seating of the machine misaligns under load.

Plate 8
Concrete cube failed on one side due to movement of the top platten of the testing machine under load.
Plate 9
Relationship between cube strength & insitu strength in concrete columns.

Plate 10
Concrete core with plastic settlement cracks and reinforcement totally useless to use for estimation of insitu concrete strength.
Plate 11
Uniform weathering of striated concrete after 40 years exposure to an aggressive city environment.