Fundamentals of Concrete

by

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Course 095

3 PDH (3 Hours)

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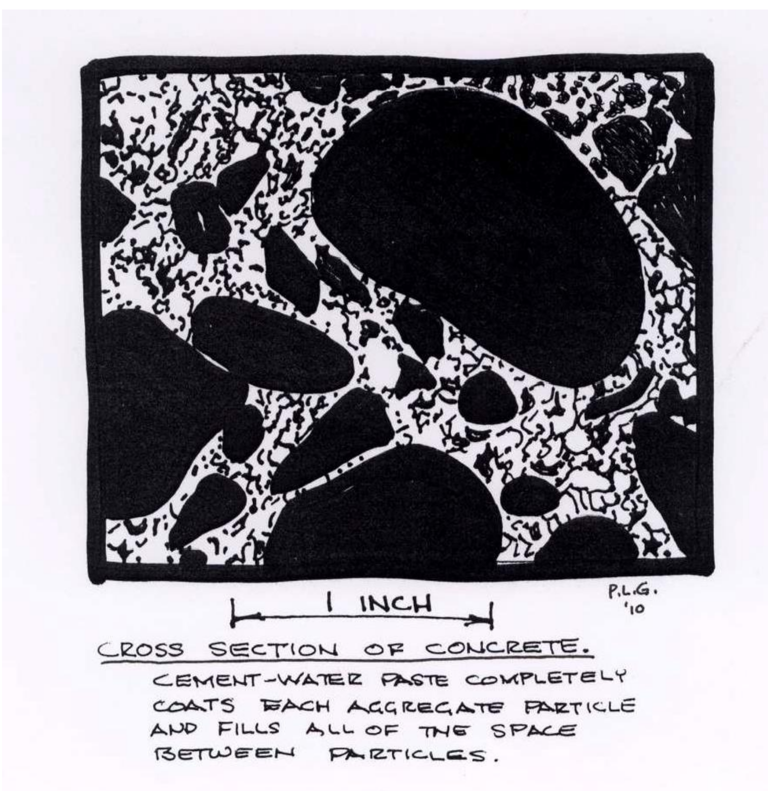
1. Composition

Concrete is a manufactured construction material. It is a heterogeneous material composed mostly of three ingredients –aggregate, cement, and water. When these three ingredients are mixed together, the material "concrete" is formed. Note that the end product is NOT cement as it is commonly called. The end product is concrete. Cement is but one ingredient in concrete.

Concrete consists of aggregate bonded together by a paste made from Portland cement and water. Each particle of aggregate is completely coated with paste and the paste fills the voids between the aggregate. After the newly mixed concrete is placed, it hardens to form a solid structural material.

A cross section through a sample of concrete looks like the following:



The aggregates used in making concrete are hard, inert materials. They have inert chemical properties. They just take up space. Aggregates compose about 75% of the volume of concrete. When making concrete, it is important that the aggregate be free from impurities. The aggregate must be clean.

The aggregates used in making concrete consists of both fine and coarse aggregate. The fine aggregates are usually defined as pieces less than and including ¼" in diameter – usually sand. The coarse aggregates are pieces larger than ¼" in diameter – usually gravel or crushed stone. It is important that the aggregate is well graded (i.e. grain size varies uniformly from large to small) to enable the smaller grains to fill the voids between the larger grains of the coarse aggregate. Other aggregate made from expanded shale or clay and slag can also be used in making concrete.

Cement used in making concrete may be obtained from nature (natural cement) or it may be manufactured. When manufactured, and it conforms to certain specifications of the ASTM, it is called **Portland cement**. Portland cement used in making concrete is manufactured from limestone. The limestone is crushed, heated and ground to a powder. Small amounts of lime, silica, alumna, and some other ingredients are added to influence the properties of the end product of cement.

There are several types of Portland cement – each imparting different properties to the concrete mix. Some common ones are:

- Class I - Normal Portland cement – used for normal concrete
- Class II - Modified Portland cement – used when low heat of hydration is required in massive pours such as large footings, etc.
- Class III - High-early-strength Portland cement – used when high strength is required in a short time.
- Class IV – Low-heat-of-hydration Portland cement – used for very large pours such as dams.
- Class V – Sulfate-resistant Portland cement – used when concrete will be exposed to a high alkali content material such as soil.

Most concrete used in buildings is made from Class I, Normal Portland cement. Some Class III, high-early-strength Portland cement, is also used.

The amount of cement in a concrete mix is usually specified in terms of sacks per cubic yard of concrete. One sack is one cubic foot of cement and it weighs 94 pounds. Most standard mixes contain a minimum of 5 ½ sacks of cement per cubic yard of concrete.

This is commonly referred to as 5 ½ bag mix. E.g., 4 yd^3 of 5 bag mix contains 1,880# of cement. 4 cyd x 5 bags/cyd x 94#/bag = 1,1880#

The water used in making concrete must be clean and free from large quantities of oil, grease, acids, sugar, organic matter, and other impurities. Basically, the water must be potable – drinkable.

The amount of water used in a concrete mix will vary depending on the use of the concrete. However, standard mixes have a maximum of 6 ½ gallons of water per sack of cement. The water-to-cement ratio is very important in designing concrete mixes. Because it is so important, care must be taken to add only the proper amount of water to the mix. In fact, it is so critical that the surface water clinging to the aggregate must be taken into account to insure a proper mix. If you are using damp sand, for instance, you must reduce the amount of water added by a similar amount of water already in the damp sand.

Concrete is an economical material to make because aggregate, cement, and water are available nearly everywhere.

2. WEIGHT OF CONCRETE

The weight of a batch of concrete is dependent on the specific ingredients used in the mix. For example some mixes can weigh as much as 160 pounds per cubic foot. Conversely, if a lightweight aggregate is used, the mix can weigh as little as around 75 pounds per cubic foot. However, unless there is something special about the particular mix, concrete is assumed to weigh 150 pounds per cubic foot. This weight includes the various amounts of cement, water, aggregate, and any reinforcing steel (which we will discuss later).

3. CHEMICAL REACTION

The "life" of concrete begins when the water mixes with the cement in a batch of concrete. When this mixing occurs, a complex chemical reaction is started. This reaction continues for a long time and is called **hydration.**

Once the water is added to the cement in a batch of concrete, an internal time clock begins. The chemical reaction begins in earnest in about half an hour under favorable conditions (mostly warm temperatures). When using a normal concrete mix with Type I cement, the concrete should be in place within 1 ½ hours after the water is added to the Ready-Mix truck.

Immediately upon mixing the ingredients for a batch of concrete, the form of the material takes on a liquid or plastic consistency. It will have flow characteristics similar to lava from a volcano, in that the material can be poured, mixed, and shaken. The concrete mix must be contained like a liquid during the first hours and days of its life. When the newly mixed concrete is poured out of the mixing container, it will flow and take the shape of whatever was built to contain the concrete mix.

As concrete cures it loses its plasticity and changes to a solid. The biggest factor in the rate of change from plastic to solid is the temperature. Warmer temperatures mean that the chemical reaction will occur faster and the mix will change to a solid quicker. Cooler temperatures mean it will take longer to change from a plastic consistency to a solid. If concrete is allowed to freeze before it is properly cured, the chemical reaction will essentially stop and the frozen area of concrete will be ruined.

As the curing process takes place, heat is given off – the heat generated by the chemical reaction. This heat is called the "heat of hydration". In massive pours, like concrete dams, this heat of hydration is an important consideration in the curing of concrete. It must not be allowed to build up as excessively high temperatures will ruin concrete.

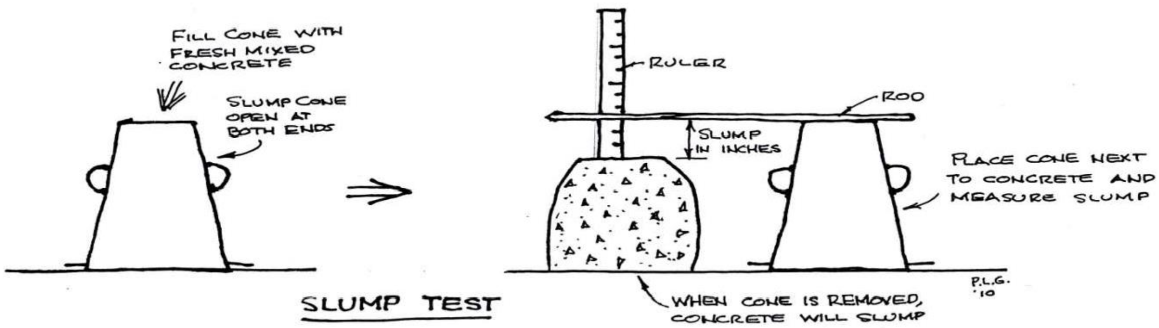
4. ADMIXTURES

When a batch of concrete is made, several additives, or **admixtures**, can be added to the mix. These admixtures affect the rate of hydration as well as the properties of the final hardened concrete. There are many admixtures available. Admixtures can be used to retard the curing time required, to lengthen the curing time, to increase the strength, to increase its resistance to abrasion, and to increase its resistance to oils, greases, acids and other contaminants. And other admixtures can be added to the mix to affect other properties of the hardened concrete as well.

5. WORKABILITY

Workability is the ability of a plastic mix of concrete to be placed in a manner that will permit the most thorough compacting and working into all the recesses of the form. Depending on the amount and type of ingredients in a batch of concrete, the initial, plastic mix will have different consistencies. And depending on its consistency, the workability of the concrete will be affected. This is an important characteristic of the mix to insure proper placement and finishing of the concrete.

A **slump test** is used to determine the workability of concrete. A slump test is easily done by placing fresh concrete in an inverted cone which is open at both ends. When the cone is lifted off, the concrete will slump, or fall a bit. The amount of fall, or slump, is measured with a ruler - the less the concrete slumps, the stiffer the mixture. The slump of a concrete mix is given in inches. For example, a batch of concrete with a 4” slump means the concrete fell 4” when the slump cone was removed. This batch is called “4” slump concrete”. A 4” slump concrete is stiffer than a 6” slump concrete.



6. STRENGTH OF CONCRETE

Class I cement will make concrete which will have nearly all of its strength in about a month and Class III cement will make concrete which will have nearly all of its strength in just a few days.

Concrete has an ability to resist compressive forces. It has a high ultimate compressive strength. It does not, however, have the ability to resist large tensile forces. Because the compressive strength of concrete is so large compared to the tensile strength, we generally consider concrete to have no strength in tension.

The compressive strength of concrete is important in the construction of concrete structures. The principle factors affecting the compressive strength of concrete are the water-cement ratio and the extent to which hydration has progressed.

Concrete gets stronger as time goes on. The standard time used to measure the strength of concrete is 28 days. We refer to the 28 day strength of concrete as its strength. For example, 3000 pound concrete means that a mix of concrete will have an ultimate strength of 3000 pounds per square inch (psi) in compression in 28 days.

The ultimate strength of a batch of concrete is determined by casting a standard 6" round by 12" long concrete cylinder at the time of placement of that particular batch of concrete. Then, after 28 days the sample is put in a testing machine and loaded to failure in compression. It is crushed. The ultimate stress that the sample withstood is calculated by dividing the load by the area of the cylinder.

For example, a round cylinder has an area of $A = \pi r^2$. For a 6" diameter cylinder, the area is (3.14) x $(3)^2$ = 28.26 in^2. Say at 28 days a concrete sample cylinder withstood a force of 100,000# before crushing. The stress at failure – the ultimate stress – would be

100,000# ÷ 28.26 in^2 = 3,538 psi.

Remember that the concrete was mixed 28 days ago and had hardened, or cured, or hydrated to this strength on this day.

As it turns out, we can predict the 28 day ultimate strength of a concrete mix well in advance of the 28 days. If we test a cylinder at say, 3 days, we can predict fairly accurately what the 28 day strength will be. If we wait for 7 days to test the cylinder, we can predict the 28 day strength more accurately than at 3 days. This is frequently done to determine if the proper concrete was delivered to the job site. If the concrete delivered to the jobsite is structurally inadequate because of an improper mix or because of adding too much water to the batch before placing, we want to find out as quickly as possible. There will then be time to remove and replace it with suitable concrete and not delay the job for an unreasonable length of time.

The quantity of water relative to that of the cement is the most important item in determining the strength of normal concrete. This is known as the **water-cement ratio**. As the amount of water relative to cement is increased in a concrete mix, the strength of the concrete goes down. As the amount of water relative to the amount of cement in concrete is decreased, the strength of the concrete goes up.

The water-cement ratio is also an index to the durability, water tightness, and workability. As the water-cement ratio increases, the strength, durability, and water tightness of the final hardened product decreases. And, the workability of the concrete in the plastic state increases - it becomes easier to work i.e. to place in the forms and to move around.

As an example of how the water-cement ratio affects the strength of concrete consider that if a batch of concrete is mixed using about 5 gallons of water per sack of cement, the resulting mixture will attain a 28 day strength of about 4,000 psi. If everything were kept the same in this mix EXCEPT that we used about 8 gallons of water per sack of cement, the resulting mixture would have a 28 day strength of only about 2,000 psi.

The strength of concrete is also influenced by the strength of the aggregate used. If the aggregate used in the mix is weaker than the hardened water/cement paste, then during the compression testing, the aggregate will break before the hardened paste. The ultimate strength of the hardened concrete will be determined by the strength of the aggregate.

If the aggregate is stronger than the hardened water/cement paste, then the paste will break first. The ultimate strength of the hardened concrete will be determined by the water-cement ratio used in the mix.

A wide range of strengths of concrete can be made. The physical properties will vary over a wide range compared to other structural materials.

7. EVAPORATON - A FACTOR AFFECTING THE STRENGTH OF CONCRETE

It is important that the water in the concrete mix is not allowed to evaporate until the curing, or hydration process is well along. The chemical process during hydration requires water to continue in a proper manner. The water is “used” in the curing process and any water that evaporates is not available for the hydration to continue to completion. If the water is allowed to evaporate during the curing phase, the water-cement ratio will change and the process of hydration will be altered. This, of course will affect the strength of the concrete but it will also affect other properties of the cured concrete.

Various techniques are used to keep water from evaporating from freshly placed concrete. Placing visqueen over a freshly placed slab of concrete stops all evaporation. Sometimes a compound is sprayed on the freshly placed concrete to prevent evaporation. Others will use a layer of burlap cloth or a thin layer of straw to cover the concrete and then keep the material wet with a spray of water. These techniques should be implemented for one to two weeks after the concrete has been placed, depending on the weather.

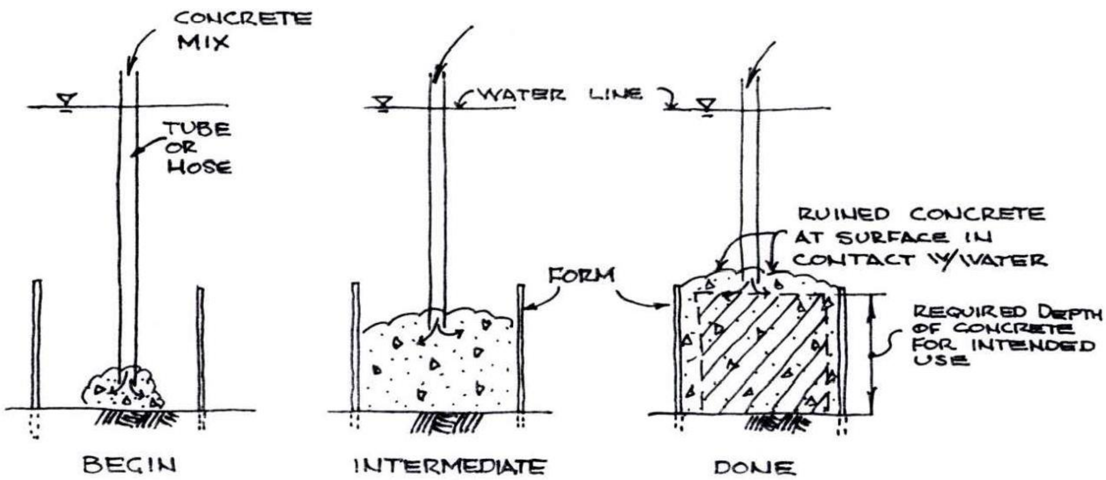
Slabs of concrete such as sidewalks, drive ways, streets, or patios are especially susceptible to loss of water through evaporation because there is a relatively large area of exposed concrete surface compared to the mass of the concrete. The structures are thin relative to their exposed area and the loss of water can be quick and excessive especially on a sunny, hot, and windy day. In addition to the rapid water loss, the curing process is moving along at a fast pace because of the sun and higher temperature. And, the curing process – the chemical reaction – needs the water that is being lost through evaporation. Consequently, the concrete should be placed and finished quickly and then immediately covered and protected from evaporation when the weather is hot, sunny, and windy.

Ideal curing conditions for concrete are a warm and moist environment. Some beam manufacturers will create a curing room where the air temperature is high and the humidity borders on 100%. Others will use steam to create a warm and moist environment.

<u>Placing concrete under water is an acceptable and very effective way to prevent loss of water during the curing phase of concrete</u>. Obviously, water will not evaporate from concrete that is curing under water. There are a few cautions that come with placing such things as foundations and piers under lakes and rivers. One is that the water temperature may be low. This will increase the time for the curing process to run its course. It will take longer to reach its ultimate strength than it would under normal temperatures.

Another caution is that the water should not be moving over the in-place concrete. Water flow over fresh concrete will wash away the cement paste and the fines from the mix resulting in ruined concrete along the surface in contact with the moving water.

Concrete placed under water must be placed so the final usable concrete does not come in contact with the water. This is done by pumping the concrete paste through a tube, pipe, or hose to the bottom of the pour in the form. Concrete is then continuously pumped through the tube being careful to not allow the end of the tube to come out of the mass of concrete previously placed. The mass of concrete “grows” as more and more concrete is pumped though the tube until the form is full. Of course, the concrete at the top of the mass is continually moving upward through the water as more concrete is pumped into the mass. This leading surface of concrete will lose its water-cement paste as well as some fine aggregate as it flows through the water and therefore be ruined. The technique used to solve this problem is to make the form deeper and wider than required knowing that the top concrete will be ruined. Then, the remaining good concrete is at least as much as is required for its intended use.



PLACING CONCRETE UNDER WATER

For an excellent example of placing concrete under water, go to the book Mighty Mac The Official Picture History of the Mackinac Bridgeby Lawrence A. Rubin, Wayne State University Press, 1958.

8. UNREINFORCED CONCRETE

Any concrete without reinforcing steel is called unreinforced concrete. Some examples of unreinforced concrete are patios, sidewalks, and some wall footings for very small buildings.

9. REINFORCED CONCRETE (AND REINFORCING STEEL)

Reinforced concrete is concrete that has been reinforced with steel in the areas where tensile forces will exist. Hardened concrete is assumed to have no strength in tension. To overcome this property of concrete, steel rods are placed in the concrete where there will be tensile stresses. This “reinforcing steel” will then resist the tensile forces in the structural member.

A simple beam when loaded with a downward load will deflect downward – it will bend. This bending causes bending stresses in the beam. These bending stresses are composed of a compressive force in the top of the beam and a tensile force in the bottom of the beam. In a concrete beam, the concrete is very capable of resisting the compressive force in the top of the beam because concrete is very strong in compression. The tensile forces in the bottom of the beam, however, will crack the concrete because concrete cannot resist tensile forces. Therefore, to make the beam structurally sound, reinforcement must be placed in the bottom of the beam. This reinforcement is, of course, the **reinforcing steel**.

Reinforcing Steel

Long ago, reinforcing steel was manufactured in both round and square shapes. Square shapes are no longer used – all reinforcing bars are now round. The round shapes are deformed – they have small "bumps", or deformations, around the perimeter of the rod to help the concrete "grab" the rod. When steel is in tension, it wants to pull out of the concrete. The bond between the concrete and steel must be large enough to overcome this pull. The deformations provide a mechanism to help this happen.

There are various common, or slang, names for reinforcing steel. Depending on where you are and who you are talking with, reinforcing steel may be called reinforcement, re-rod, re-bar, re-steel, bars, or rods. The terms are used interchangeably, sometimes in the same sentence.

The reinforcing bars used in "normal" reinforced concrete beams can have allowable working stresses of 20,000 psi to 33,000 psi. However, reinforcing steel is also available in deformed bars with ultimate strengths of 100,000 psi, and more. These bars are made from billet steel and are for use in concrete structures designed to require reinforcement with a high yield point.

The following table shows the standard properties of reinforcing steel used in the design of concrete members. The left column is the bar number (identified as either # or No.). For #2 through #8 bars, the number coincides with the bar diameter in eights of an inch. For example a No. 5 bar has a diameter of 5/8 ". For larger bars, the numbers are simply designators. The second column is the weight of the bar in pounds per foot.

The third column is the diameter of the bar. The fourth column is the cross sectional area of the bar and the last column is the perimeter of the bar.

WEIGHT, AREA, AND PERIMETERS OF INDIVIDUAL REINFORCING BARS

BAR SIZE	WEIGHT (Pounds per Foot)	DIAMETER (Inches)	CROSS SEC. AREA (Sq. In.)	PERIMETER (Inches)
#2	.167	.250	0.05	.786
#3	.376	.375	0.11	1.178
#4	.668	.500	0.20	1.571
#5	1.043	.625	0.31	1.963
#6	1.502	.750	0.44	2.356
#7	2.044	.875	0.60	2.749
#8	2.670	1.000	0.79	3.142
#9	3.400	1.128	1.00	3.544
#10	4.303	1.270	1.27	3.990
#11	5.313	1.410	1.56	4.430

WWM and WWF

Certain concrete placements do not need reinforcing steel to resist the tensile forces that are generated by live and dead loads – because there are none, or they are very small. Residential basement slabs and driveways, patios, and other flat structures not subjected to heavy loads are fully supported by the soil on which they rest. If the soil under the slabs is properly prepared, they will not incur large bending stresses.

However, an important property of concrete that must be acknowledged, and planned for, is the fact that concrete cracks. All concrete cracks. The very act of hydration causes small shrinkage stresses which in turn cause small cracks in concrete. The cracks in concrete slabs can be so small that they can only be seen through a microscope, or so large that weeds can easily grow through a concrete drive.

In thin slabs exposed to the weather – driveways, and patios, for instance – a wire mesh is placed in the concrete during placement to prevent the cracks from opening up. Essentially, the mesh holds the chunks of concrete tightly together to prevent unsightly cracks from opening up.

The mesh or fabric is made by running longitudinal and transverse wires at 90° to each other and spot welding them together. The common wires sizes range from a relatively small No. 10 to a relatively large No. 2, and the spacing of wires in the mesh generally range from 2” to 6”.

After fabrication, the wire grid is then rolled up and delivered to the jobsite. At the jobsite, the wire is unrolled and placed in the form prior to placing the concrete.

The wire grids are referred to as “welded wire mesh” or “welded wire fabric” and are abbreviated as WWM or WWF. The size of the wire and spacing is also noted when calling for the product. A commonly used wire mesh product is referred to as 6x6x10/10 WWM. This means the grid size is 6” by 6” and the wires are No. 10 wires each way.

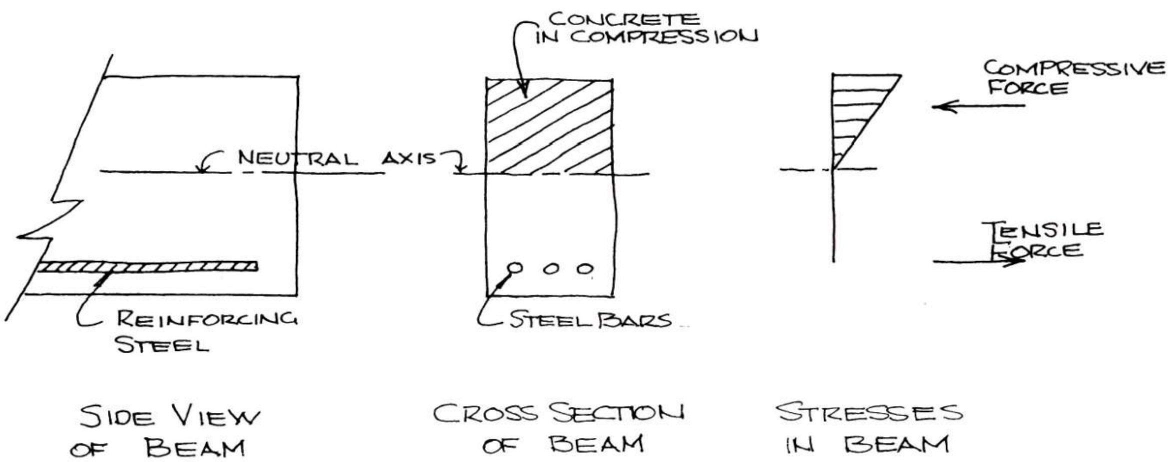
When the wire fabric is placed in the concrete, it is pulled up to approximately the middle of the slab thickness as the concrete is placed. The wire mesh will also resist some tensile stresses that may be introduced because of soft soil spots.

Concrete floors in buildings supported by steel joists and metal decking, on the other hand, do have bending stresses in the concrete. These floors need to be reinforced with welded wire fabric. In this case the mesh is definitely reinforcing steel.

10. COMPRESSION AND TENSION IN A CONCRETE BEAM

The theory behind the design of a reinforced concrete beam is quite complex. The formulas used in the computations are numerous and dependent on the type and strength of concrete, the type and strength of steel used, the ratios of the Modulus of Elasticity of the two materials, the shape of the beam, and other factors beyond the scope of this course. Also, the design of some reinforced concrete members is not a direct calculation. It is a trial and error approach. For the anticipated design loads, a size of member is selected and it is analyzed. If it does not conform to all design criteria – such as percentage of steel, allowable stresses, surface area of steel to concrete interface, anchorage, space between bars, etc., - another size and type of member is selected, and the analysis done again. There are numerous tables and charts available in workbooks and handbooks to aid in the design of concrete members. However to illustrate the concepts of the concrete resisting the compression forces and the steel resisting the tensile forces in a beam, the following is presented.

The stresses in a simple span reinforced concrete beam can be approximated by the following sketch. The first diagram is a side view of a beam showing the placement of the steel rods in the bottom of the beam. The second diagram shows a cross section of the reinforced concrete beam. And the third diagram shows the approximation of the stresses and forces in the beam.



The compressive force is acting over the entire face of the concrete beam above the neutral axis. The maximum stress (in this design assumption) in the concrete occurs at the extreme fiber – the top of the beam and there is zero stress at the neutral axis. The tensile force is assumed to act only at the location of the reinforcing steel.

Let's assume that after careful analysis, the total compressive force allowed on the compressive face of the beam is 50,000 pounds. Since the sum of the horizontal forces must total zero on the cross section of the beam, the tensile force in the steel must also be 50,000 pounds. The question we will consider now becomes "How much reinforcing steel is required to resist the tensile force?"

Let's assume that because of other design considerations, we must use No. 5 rods. And that the working stress of the reinforcing steel is 24,000 pounds per square inch. How many #5 rods are required to resist the tensile force of 50,000 pounds?

Tension Force = (area of steel) x (working stress of steel)

50,000 # = (area of steel) x (24,000 psi)

Area of steel required = 50,000# / 24,000 psi

= 2.08 square inches

From the table of properties of reinforcing steel, a No. 5 bar has a cross sectional area of 0.31 square inches. Therefore,

Number of No. 5 bars = (total area required) / (area of one bar)

= (2.08 square inches) / (0.31 square inches/ No. 5 bar)

= 6.7 bars. Since you can't use 0.7 of a No. 5 bar, you must round up to the next full bar. Therefore use 7 No. 5 bars.

<u>USE 7 No. 5 bars</u>

11. CAST-IN-PLACE CONCRETE

Cast-in-place concrete describes the concrete that is put into the form in the location that it will be used. For instance, if you were going to make a concrete patio, you would first build a form out of 2 x materials, place the wire mesh in the forms, and then place the concrete in the forms. After the concrete had cured, the forms would be removed and the patio would remain in place. This is an example of a cast-in-place structure. Another example would be a poured basement wall. Here again, the forms are built, reinforcement steel put in place, and the concrete added. After proper curing time, the forms would be removed. The concrete remains in place.

In the construction of a reinforced concrete beam, a form is built, the steel is placed in the form in the proper position, and the concrete is placed in the form. Once the concrete is placed in the form and compacted and worked into all the crevices and recesses of the form, including in complete contact with the reinforcing steel, it is allowed to cure. Then, when the concrete has cured, the forms are removed and the beam is ready to perform. This performance is simply to resist, or support, the loads it was intended to carry.

Many times the floor and supporting beam and column system are cast-in-place as a unit. This system requires elaborate forming systems. Many large buildings have the columns, beams, and floor system tied together in this way.

Here is an example of a cast-in-place concrete building under construction.

12. PRECAST CONCRETE

Precast concrete is concrete that is placed in the form at some location other than where the concrete member will be used. For example, many beams (and columns too) are made at a precast concrete plant (read “concrete beam factory”) and then transported to the site for use in the building or bridge. This is very economical when you have several pieces of the same size and shape. Parking garages are typically made from precast beams and columns. Also the walls of some buildings are precast concrete panels. The panels were cast somewhere else, transported to the building site, and then attached to the building frame.

A big advantage of using precast beams is that the time needed to construct the project can be reduced. The beams can be manufactured in advance of when they will be needed on the job site. The delivery can be staged so that beams arrive on the site as they are needed – a continuous supply of structural members ready to use. There is no on site forming, placing of concrete, and waiting for curing to take place.

There are three popular types of precast beams, each with variations. There are precast beams with regular reinforcement; precast pre-stressed beams; and, precast post-tensioned beams.

Precast Beams with Regular Reinforcement

The predominate precast beam with “regular” reinforcement is the precast reinforced concrete lintel for masonry walls. These beams are quite common and typically range in lengths of from 4 feet up to around 12 or 13 feet. They are nominally 4”, 8”, and 12” wide and are used to support block masonry above openings in the masonry wall. They are a standard shape and design and are readily available at the masonry supply yard.

Precast Pre-stressed Beams

A regular reinforced concrete beam is subjected to compressive forces in the concrete and tensile forces in the steel as soon as the form is removed. The beam must immediately carry its own weight. As it turns out, the limiting factor in the weight carrying capacity of a regular reinforced concrete beam is the capacity of the concrete to resist the compressive stresses. The required cross sectional area of the concrete versus the required cross sectional area of the steel to resist essentially the same forces is considerable. It takes a much larger area of concrete to resist the same force as a small area of steel.

To use some of the concrete’s capacity to resist compressive forces just to carry its own weight, and other dead loads, can reduce the live load carrying capacity of the beam to a significant degree. Also, as the compressive and tensile forces get larger in a regular reinforced concrete beam, a corresponding increase in cross sectional area of the concrete and steel must occur. The problem is that the area of concrete quickly grows unwieldy. The beam can become too large to be used efficiently and effectively. The steel, on the other hand, can be increased significantly with very little increase in beam size. There is usually no problem allowing the steel to resist these dead load forces.

With this in mind, it becomes clear that if we can somehow create a beam that can carry its own weight - and some or all of the additional dead load to be carried - without "using up" any of its compression carrying capacity of the concrete, we could have a beam of the "same" size that is capable of carrying much large applied loads, both dead and live.

In fact, we can create a beam that can carry the dead load without using any of its compression carrying capacity. The beam is a pre-stressed concrete beam.

A pre-stressed concrete beam is always precast. In a precast pre-stressed concrete beam, the steel is actually stretched (stressed) before the beam is cast. The form is built and pre-stressing cables are stretched through the bottom portion of the form. They are stressed – pulled tight – elongated – usually with hydraulic jacks. Then, with the cables still tight, the concrete is added to the form. The cables must continue to be pulled - stressed - while the concrete is curing. Then, when the concrete has cured sufficiently, the forms are removed, the cables are connected to the ends of the beam, and the jacks are released. When the cables are cut loose, they want to shorten back to their original length. But they can't because they are fastened to the ends of the beam.

What happens at this point is that compressive stresses are induced into the concrete in the bottom half of the beam. If there are compressive stresses in the bottom half of the beam, there must be tensile stresses in the upper half of the beam. And, in fact, there are. Now we have a beam sitting there, supporting its own weight, with tension in the top and compression in the bottom and all because of the pre-stressing cables in the bottom of the beam.

To resist the tensile forces in the top portion of the beam, the top of the beam must be reinforced with conventional reinforcement.

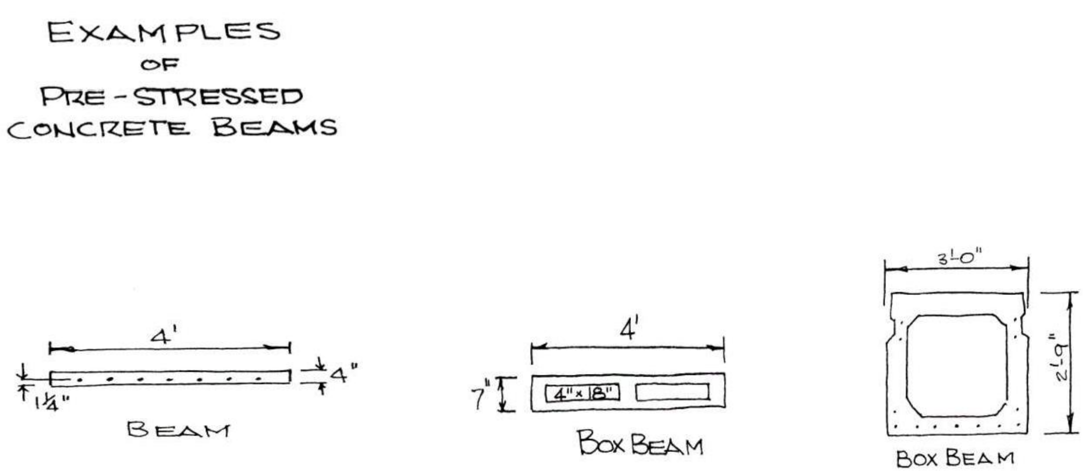
All pre-stressed beams are simple spans. When the cables are "cut loose" and compression is induced into the bottom of the beam, the beam can "pop up" a bit. The center of the beam can lift off the bottom of the form. And the beam would then be supported only at the ends – a simple span beam.

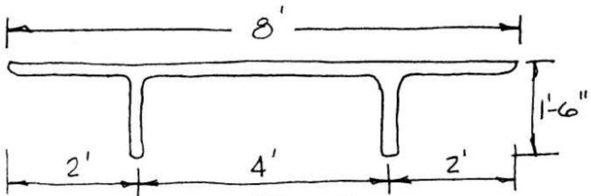
The main consequence of this situation is that the beam is much stronger than a conventionally reinforced beam. Remember in a conventionally reinforced beam some of the concrete capacity is used to carry the dead load. In a pre-stressed beam the concrete in the top of the beam starts in tension and as the dead load is added the tensile stresses in the concrete go down! If the beam is designed in a certain way, when the beam is carrying all of the dead load, the concrete in the top half of the beam will have no stress! Now, all of the concrete capacity is available to carry live loads.

An important component of making this scheme work is using pre-stressing wire for the steel reinforcement. Pre-stressing wire is very strong. It has an ultimate stress of about 270,000 psi and a working stress of about 200,000 psi.

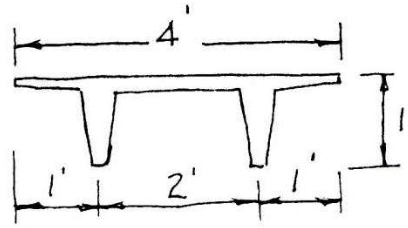
Because high strength steel is used for pre-stressed beams, the required area of steel necessary to resist the tensile forces is small. And, because the steel area is small, the volume of concrete in the tension side of the beam - below the neutral axis - can be reduced considerably. The size of the concrete can be quite small. This concept has resulted in many different shapes of pre-stressed beams.

Following are drawings representing several different shaped pre-stressed beams. The dimensions shown are representative of the various possibilities of beam sizes.

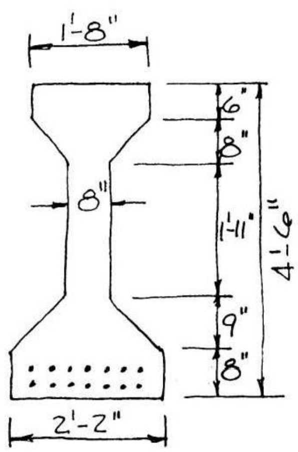




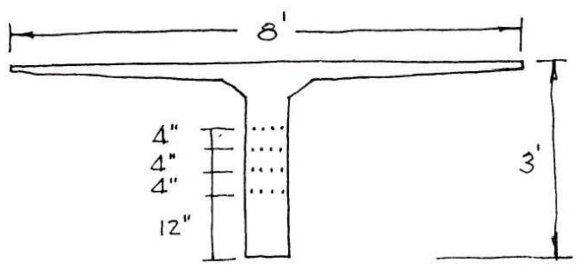
DOUBLE TEE BEAM



DOUBLE TEE BEAM



I BEAM



TEE BEAM

The following photo shows several precast, pre-stressed concrete I-beams supported by a bridge pier.

The following photos show some pre-stressed box beams on a truck being delivered to a construction site, and shows the beams in place – being used as a floor in a building.

Precast Post-tensioned Beams

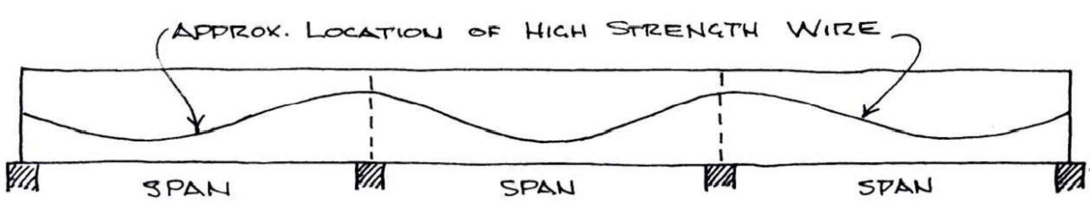
Precast post-tensioned beams are beams where the high strength wires are stressed, or stretched, after the beams are in place. These beams can be used very effectively for continuous spans.

The manufacture of these beams is similar to the precast pre-stressed beams except that instead of placing the steel in the form and stretching it before the concrete is placed, tubes to receive the steel wire are placed in the forms before the concrete is placed. Then, after the concrete has been placed and cured, the forms removed, and the beam delivered to the site and set in place, the pre-stressing wires are then threaded through the tubes and then stretched – or stressed. They are post-tensioned.

Several beams can be placed end to end over several supports creating a continuous beam. In this case, the tubes to receive the reinforcing wire are positioned to allow the reinforcing wire to be in the proper location to resist the tensile stresses in the continuous beam – namely in the bottom of the beam near the center of the spans, and in the top of the beam over the supports. After the beams are in place, and appropriate anchorages are in place, the high strength reinforcing wire is threaded through the "continuous" beam and stretched or tensioned. This creates a continuous beam over several supports.

Post-tensioned beams are most commonly used in bridges. When building a bridge using post-tensioned, continuous span beams, the beams are initially simple spans. It is only after the steel is threaded through the tubes and tensioned – from end to end of the several simple spans – does it actually become a continuous beam.

The following sketch shows the relative locations of the post-tensioned steel in a three-span continuous beam.



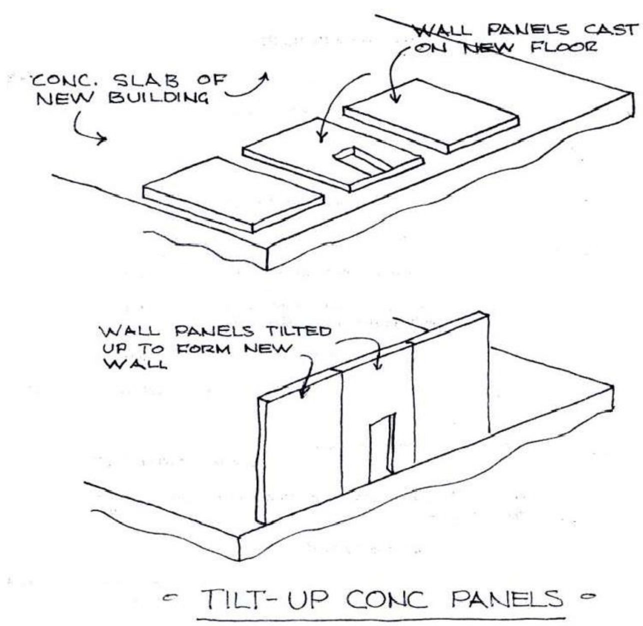
3-SPAN CONTINUOUS PRECAST POST-TENSIONED BEAM

Precast Panels

Precast panels are used to construct the exterior walls of buildings. The panels are usually manufactured in a precast plant specializing in panels and shipped to the site for installation. The panels are set in place, anchored, and function as the wall. The exterior side of the panel can be finished in several different patterns and textures.

Some single story buildings are built using what is called tilt-up construction. In tilt-up construction, the panels are precast on site, and erected to form the walls of a building. The advantage of using tilt-up construction techniques is that the panels are formed and poured using the newly constructed floor slab as the base for the formwork. First the floor slab of the building is placed and properly cured. Then the concrete panels are formed on the slab by using steel forms to form the edges of the panels – the floor is the bottom of the form. Then the concrete for the wall panels is placed in the forms and allowed to cure. After proper curing, the edge forms are removed and the wall panels are then tilted up, set in place, and fastened together to form the walls of the building. They were pre-cast on the floor of the building.

The schematic below shows the essence of tilt-up construction.



13. FORMWORK FOR CONCRETE

The fact that concrete begins its existence as a plastic material makes it a very useful building material. Concrete will take the shape of its form before turning into a solid structural member. To make structural members out of concrete, you must be able to build a form to hold the wet mix until it can cure and reach a suitable strength. In essence, if you can build a form for it, you can make it out of concrete. Formwork design is a specialized field of structural engineering.

During the first few hours and days of its life, concrete will change from a liquid, or plastic like material, into a solid material. It is during this time that the forces on the formwork are the greatest. When pouring a wall for example, the formwork is relatively tall compared to the thickness of the wall. When concrete is placed in the form, it obviously flows to the bottom of the form and begins to fill up the wall form – it gets deeper in the form. Because the concrete has some of the properties of a liquid, the initial pressure on the bottom of the form is directly proportional to the depth of the concrete in the form – the deeper the concrete, the greater the pressures at the bottom – just like in a swimming pool. The deeper you go under water, the greater the pressure in all directions.

When concrete is initially mixed, it has no strength. It acts like a liquid. As time passes, the chemical reaction caused by mixing water with cement causes the concrete to harden and gain strength. This phenomenon is important when placing the concrete in the relatively tall forms – like walls and columns, for example.

If the concrete in the form gets too deep too quickly, the pressures can increase to a point where they exceed the ultimate strength of the form material and the form will bow or bulge out, or in a worst case scenario, the bottom of the form will “blow-out”. The blown out form is a complete structural failure of the form and the concrete mixture will flow out and create a mess that needs to be cleaned up before it hardens into a solid lump.

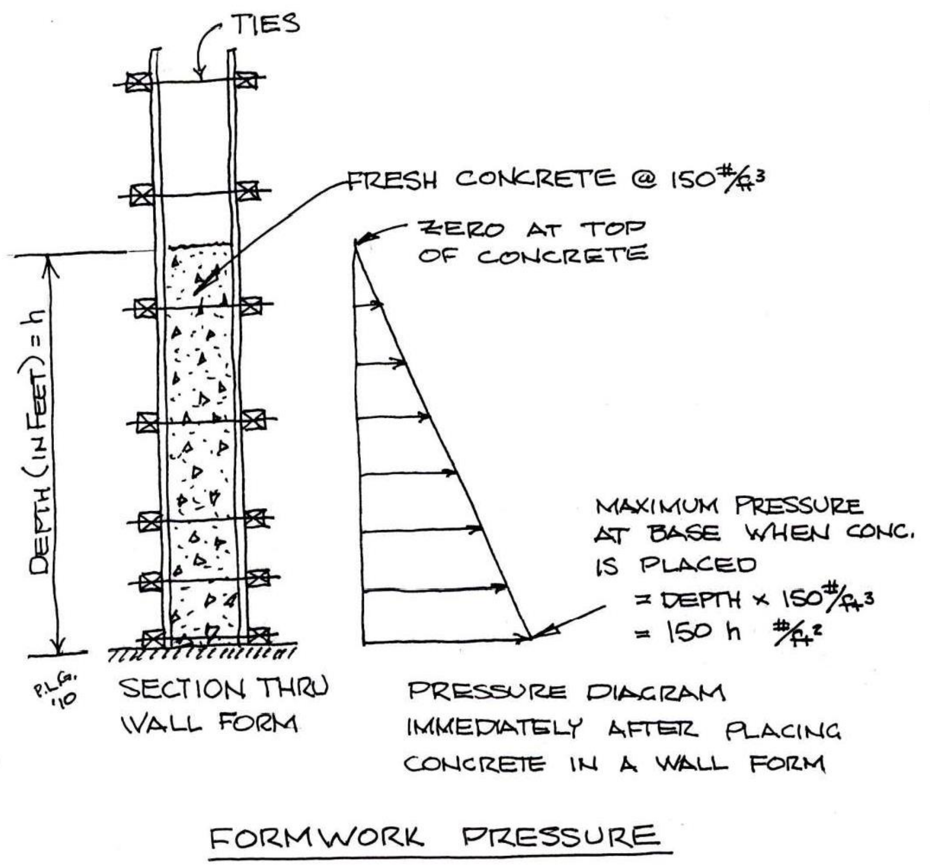
The trick is to place the concrete in the vertical forms at such a rate that the pressures at the bottom of the fresh concrete never exceed the pressures that the forms were designed to withstand. Concrete is placed in the forms to a predetermined depth and is allowed to cure for a bit to gain strength – to change from a material with plastic properties to a material that is stiffening and the outward forces on the form are gradually reducing. After some time, the concrete in the form has enough strength to withstand the added weight of fresh concrete above without transferring outward forces to the bottom of the form. This layer is then allowed to cure to the point where another layer of fresh concrete is placed on top. This process is followed until the vertical form is completely full to the required depth.

In practice, for example when placing concrete in a residential basement wall form, the concrete is placed in the form to a pre-determined maximum depth. The concrete will be placed to this depth in the entire form around the basement. It will take the workers a certain time to get around the basement placing concrete to this initial depth. When they get back to where they began the pour, they will circle the basement again adding another layer of concrete to the height of the wall. Sometimes, it may take a third time around the basement to reach the proper height of the concrete basement wall. Each pass around the basement allows the concrete in the previous layer to sufficiently cure to avoid excessive pressures on the forms.

For a given set of forms, the rate of pour is the critical factor in placing concrete in the vertical form. This is the rate at which the concrete is allowed to fill the form. It is usually expressed in feet per hour. For example, at a pour rate of 10 feet per hour, concrete will fill a form 2 feet deep in 2/10th of an hour (12 minutes).

Given a certain set of conditions – concrete mix, weather, etc. - and pour rate of 10 feet per hour, the two feet deep concrete can exert an outward force on the forms of about 300 pounds per square foot at the bottom of the form. If everything remained the same except the initial pour was 5 feet deep, the outward force on the bottom of the form would be about 750 pounds per square foot. In both cases the outward force on the forms at the top of the concrete would be zero.

The following sketch shows the lateral pressures exerted by the concrete for a pour of a certain height.



The whole area of concrete form design is a specialized area of structural engineering. Following is an example to give the flavor of concrete formwork design for vertical members. The lateral pressures of plastic concrete on wall formwork while placing concrete are a function of the depth of the concrete, the rate of filling of the forms, the temperature of the concrete, the weight of the concrete, the slump of the concrete mix, and any additives in the mix.

For the specific condition of concrete weighing 150#/ft³, 4" slump, Type I cement, no additives, normal compaction by vibration to a depth less than 4', and a rate of placement of less than 7 feet per hour in the form, the following equation governs the maximum lateral pressure on the forms:

$$P_{max} = 150 + 9000\, R/T$$

Where P_{max} = maximum lateral pressure in # per sq ft

R = Rate of fill of concrete in the form in ft per hour

T = Temperature of the concrete in °F

Assume that the concrete is being placed in the form at the rate of 4 feet per hour and the temperature of the concrete is 80°F. The maximum pressure exerted on the bottom of the form is:

$$P_{max} = 150 + 9000\ (4\ \div 80) = 150 + 450 = 600\ \#\ \text{per sq ft}$$

This means that under these circumstances, the formwork must be able to withstand a lateral pressure of 600 psf.

If everything were the same except the temperature was only 40°F, the maximum lateral pressure on the bottom of the form would be:

$$P_m = 150 + 9000\ (4\ \div 40) = \ 150 + 900 = 1{,}050\ \#\, per\ sq\ ft$$

And the forms would need to be much stronger – to be able to withstand a lateral pressure of 1,050 psf.

Again, if everything were the same except the rate of pour was 6 ft per hour and the temperature of the concrete were 80°F; the maximum pressure on the bottom of the form would be 825 # per sq ft.

And, if the rate of pour were 6 ft per hour and the temperature of the concrete was 40°F, the maximum pressure on the bottom of the form would be 1,500 # per sq ft.

The rate of pour and the temperature of the concrete are very important factors in the maximum pressure on the bottom of the forms. In cold weather, the concrete takes longer to set up and harden than it does in hot weather; therefore the pressures are greater on the formwork when it is cold. A set of wall forms that are acceptable in the summer may fail in the winter.

Also, remember that these examples are for one specific concrete mix with rates of fill of less than 7 feet per hour. Anything other than that requires a different analysis and results in correspondingly different pressures.

The acceptable rate of concrete placement in a vertical form varies according to the strength of forms and the rate of hydration of the concrete. Very strong forms and a concrete mix that cures quickly can be filled fairly rapidly. Not so strong forms and a slow setting concrete must be placed in the forms at a slower rate. Whether concrete can be placed in a form at the rate of 3 feet vertical per hour or six feet per hour is dependent on several factors and should be determined by an engineer familiar with both concrete properties and mixes and the form materials being used.

Concrete formwork for floor slabs in a multi-story building must be designed using design criteria different from that of vertical forms. However, the goal is the same - to support the concrete in its plastic state until it can cure and support its own weight. The following photo shows an instance where that was not the case. The floor formwork collapsed during the pour.

In summary, concrete is one of the most versatile materials in construction. It is easy to make, the raw materials are plentiful and readily available everywhere in the country, and it is economical. It can be used for structural members such as beams and columns, for highways and bridges, and for residential uses such as patios, driveways, basements, and swimming pools. Its uses are endless.

