Design of Masonry Structures
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Module - 02
Lecture - 07
Masonry Materials and Properties Part - III

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Good morning and we will continue looking at Properties of Masonry Mortar and that is where we had terminated in our last lecture. We are examined the properties of plastic mortar, ok. Water retentivity, workability being properties that are important as far as ensuring you get proper finish with your bed-joint mortar, which is a very important element contributing to the strength and durability of the masonry itself. The important aspect that needs to be established is the bond between the mortar and the unit.

And therefore, this is achieved through interlocking, because you are looking at, let us say you take unit- clay brick unit or a concrete block, you got undulations on the surfaces. And there is mechanical interlocking at a very small scale that is contributing to the bond, additional friction coming from the interlocking, there is chemical adhesion.

And typically, this bond must be established very soon, it is not something that will develop over time, but it is something that at the moment you cast the mortar you should expect this to start forming. And the bond itself is affected by the type of mortar that you are using, is it a high strength mortar, is it weak type of mortar, it is affected by the qualities of mortar, it is affected by the water strength ratio, it is affected by how close in strength and properties is the unit. So, compatibility matters.

Workmanship has a very important role as far as the establishment of bond is concerned, and conditions under which curing is happening for the masonry wall. You must have seen after construction, the wall has to be kept wet for a few days just like you would keep concrete wet. There is an important test that is done in the field, it is actually surprising to know that you can establish bond in such a short period of time, it is called the field bond test, it is done on the field, it is a quality control test.

And what is done is, you basically make a stack of two units with the mortar has been prepared. So, you have got the first unit, mortar and the second unit. You leave it for not more than 2 minutes, a minute to 2, and then you should be able to pick up the entire stack by just holding the top unit and it should stay. If it does not stay, bond has not been established.

So, that is why I said that initial bond has to form rapidly and that is what is actually going to initiate the process of a good quality masonry taking shape there, ok. So, this is a field bond test. It is actually done, if you have a good site engineer, you will go and check, he or she will go and check, if this can be achieved. If not, you have to throw away the mortar or check if you are units are, they might be too wet or they might be too dry. So, this is something that is good to know.

You can as we saw earlier, workability and water retentivity of the mortar is important property of the plastic state. So, if you want to improve workability, you can actually use chemicals that create air entrainment and you can actually improve the air content in the mortar mix by 12 to 18 percent, however, these can actually reduce the strength of mortar. So, one has to be careful in using these additives and with the knowledge that you can compromise strength, if you want to retain strength, you use lesser of these additives. You should be able to proceed with some of these additives if necessary, ok.

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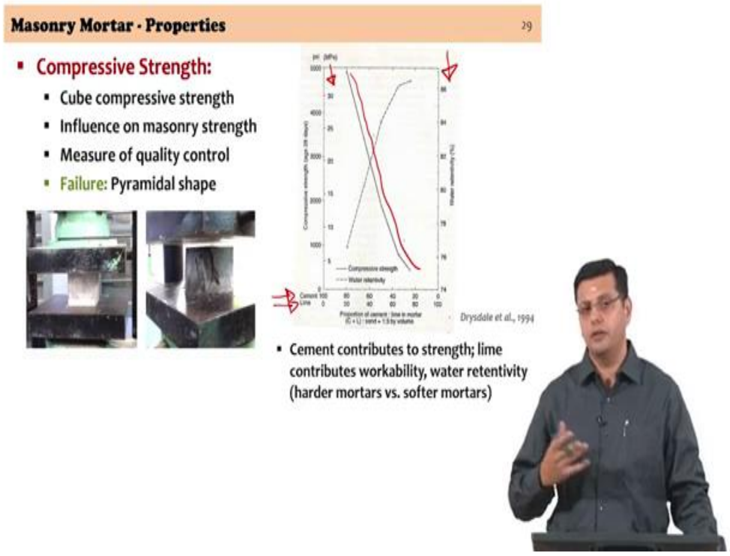

Compressive strength of mortar and again as a quality control test small cubes of mortar are cast in the site and tested, just as you would do quality control for concreting by casting those cubes or cylinders; cylinders in some other countries. So, the cube compressive strength is the parameter that we use both to classify the masonry mortar, earlier said MM 7.5 and MM 5, it is the cube compressive strength. And it is a small cube that is cast, it is a 50 mm x 50 mm side dimension.

And the masonry mortar has role, an important role to play in the compressive strength of the masonry itself. It measures the quality of the of the brick work; brick work meaning it is the assembly of brick with the mortar and typically you are looking at a cubical piece of brittle material and because of the confinement of the end plates you expect a pyramidal failure. In this typical x-shaped crack you would see because of the confining effect of the end plates, but this is a standard test procedure that we use to characterize the cube compression strength of mortar.

Now, we have talked of properties that are essential as far as the plastic mortar is concerned, and properties are essential from the hardened state. So, you have twin requirements, but you could have conflicting problems. If you make it too workable then you are going to have problems with strength. If it is if you want very high strength, water-cement ratio has to be reduced. So, you actually have you have a potential problem on hand.

And what is typically done? In case you want to have desirable properties, you want to tinker with some of these properties, what is normally done to cement is known to provide strength to mortar. Lime on the other hand, which is as you know a raw material for cement manufacture itself. Lime is not so much in use as a binding material today. But you could use lime in the composition to improve workability, but it can compromise with the strength. So, the proportion by which you add lime into the mortar mixed is typically controlled.

So, in this graph you can actually see, how as the proportion on the x-axis you have the proportion of lime and the proportion of cement. So, you could have a mortar mix which is 100 percent cement and no lime at all. And you keep reducing, the percentage of cement with lime. So, on the x-axis I go from 100 percentage of cement to 0, and lime from 0 to 100 percent.

And you are looking at the compressive strength and the water retentivity. Now, the water retentivity is an important property as we had seen earlier in the plastic state. So, if you look at the compressive strength in MPa on the inner side 5, 10, 15 upto 30 MPa and water retentivity in percentages, it becomes quite clear that, as you reduce the percentage of cement in the proportion, you keep reducing the cement percentage in the proportion, you get mortar that is more workable and has better water retentivity properties.

But you look at the reverse, what is actually happening is your strength is decreasing. The strength reduction takes place as you reduce the quantity of cement and keep adding lime. So, lime will if you are working with this pure lime, you are going to get rather weak mortar, relatively weak mortar more deformable probably, but definitely but weaker mortar.

So, this is the conflicting outcome on the final property, but plastic stage you can you can work around by changing the proportion of cement and lime or adopting a certain proportion of lime if necessary, so you could keep these in mind in working with harder mortars or soft mortars. In several cases working with the softer mortar is has shown to be much more meaningful, ok.

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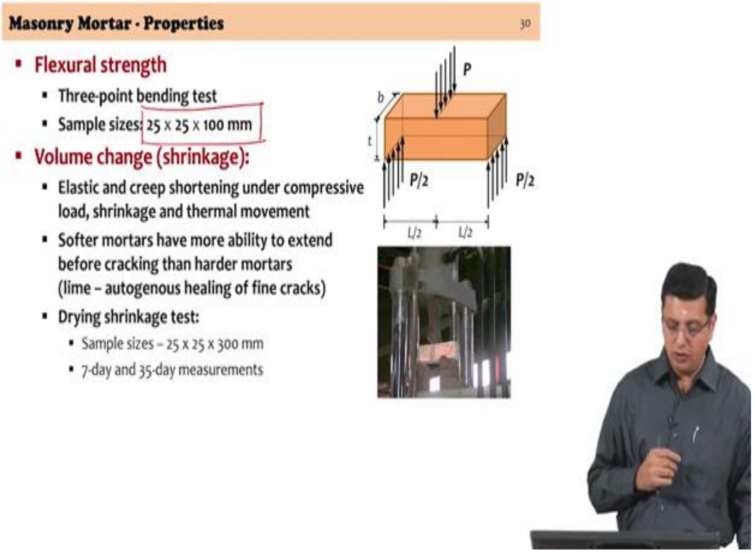

Again, compressive strength is one of the properties that you would check, but you also need to know the flexural tensile strength, the tensile strength of the mortar sample. Three-point bending test as we had looked at; the three-point bending test for the brick unit can be adopted here.

And the sample that is typically made is a sample which is of size 10 cm in length and 2.5 cm x 2.5 cm in cross section. And you load it in flexure and the stress gradient is going to give you the possibility of maximum bending stresses at the mid span and failure is brittle.

This is a brittle material and you can see how the mid span crack forms with maximum flexural tension at the bottom. This is one property that can be rather easily assessed experimentally. Another property of significance is volume change or shrinkage in the mortar. And this is again experimentally tested using a small beam made out of mortar. And then you look at what the volume change is, how much the mortar is shrinking as the hardening process is happening; at 7 days and at 35 days, and there are limits for shrinkage.

Because if mortar shrinks too much, it has established a bond with the unit; but if it shrinks too much you can have failure at the bond by the time the wall gain strength and hardenss. So, this is a fundamental problem. If there is too much of shrinkage, shrinkage cracks will develop and shrinkage cracks would not probably immediately compromise the stability of the system, but it will affect durability, because moisture penetration will commence with formation of these cracks in the mortar itself. So, we are early talking of the elastic and creep shortening as you have compressive loading and the thermal effects and the shrinkage effects together deciding how much of volume change is going to happen in the in the mortar itself.

If you have a softer mortar; the softer mortar has more deformability basically; when we call it soft it is about how deformable it is. And therefore, these are more ductile, they deform more before cracking and failing and harder mortars behave in a much more brittle manner. And it is in this context that, the softer mortars possibly achieved with the use of replacing cement with lime or just with lime, are much more desirable as their performance is concerned. And a very important characteristic of lime is observed in these situations and it is called the autogenous healing of cracks.

What actually happens is the mortar composition is such that when cracks are formed, the lime mortar has a slow process of hardening, and material is still available to go and fill up these cracks and almost close the cracks and continue to allow formation of distributed small cracks. And therefore, the deformability is something that you see much more than a hard, brittle material like cement mortar. So, this is a subject that is of significant research focus, the behavior of lime mortars. It is still not fully understood because it is a very complex chemical composition.

The autogeneous healing is something that is being steadily researched, because for repair of masonry and historical masonry, this property of lime is extremely useful. It is also being researched from the point of view of repair of other structural materials. So, this is something you might want to know. So, sample for the drying shrinkage test again as I said is a beam, here the beam is 25 mm x 25 mm x 300 mm and take measurements at two points in time 7 days and 35 days, and the mortar shrinkage should be within certain limits, ok.

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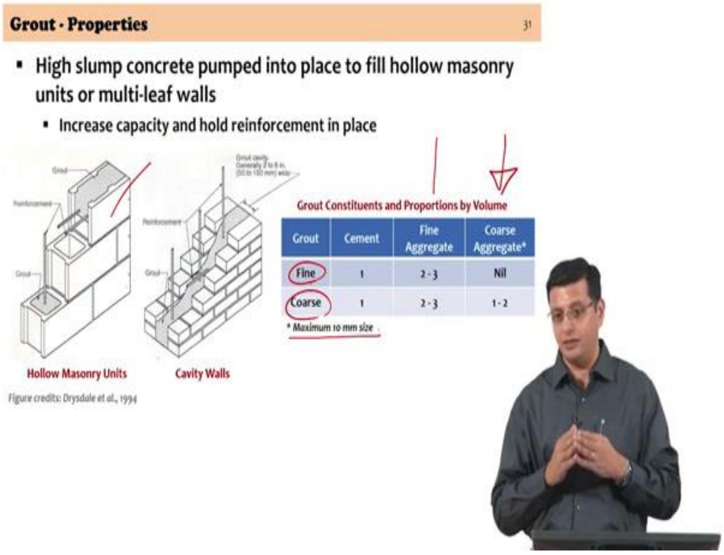

So, that brings us to two sets of constituents that we talked about and as I had mentioned earlier, grout is another important constituent of masonry construction today. The hollow blocks partly are grouted or sometimes fully grouted and when you have reinforcement, you have to grout the cavity in which you the reinforcement. So, grout itself is a different material.

If you are using concrete blocks, the chances are that the grout material that you are using is close enough to the concrete block's composition, but it still could be different. If you are using hollow clay bricks or if you are using solid clay blocks and you have cavities in which you are pouring concrete, it is a completely different a material with respect to the unit or the shell. So, this is a material that you must consider and has a role to play in the strength of the masonry, in the deformability of the masonry and is primarily there to protect your reinforcement.

Yes, your question is like we do a formal mix design for concrete, do you do a mix design for mortar? I would answer it this way, if you want to achieve a certain strength of your masonry, you can formulate the strength of the masonry by knowing the strength of the mortar and the strength of the unit. So, you choose a certain strength of mortar and a certain strength of unit and these two together are going to give you a strength of the masonry.

Now, how do you work backwards? I can say I need a unit of strength 10 7.5 N/mm^2 and I can get that manufactured. Now, mortar if I by calculation want a mortar that is 7.5 N/mm^2, it is again a composite. So, how do I achieve 7.5 N/mm^2 mortar and that is where you need to know; what proportion is required of cement, do you have any other additive like a pozzolana and lime, and the fine aggregate.

So, you break it down you want to achieve a certain masonry strength; it is directly dependent on the mortar strength and the unit strength. And therefore, since the mortar strength has to be achieved, the average compressive strength has to be achieved, you need a proportioning for that.

So, you can carry out the a process similar to mix design for concrete; however, the tables that we have seen in the other class, were depending on the strength of cement and depending on the proportions of the fine aggregate and the cement, you will get a certain average compressive strength which is typically what is done. So, strictly speaking you would not be doing a mix-design every time, you would be depending on these readymade tables to guide you how to choose the mortar itself, right.

So, as far as the grout is concerned, you are looking at concrete that is high slump concrete. You typically pump it into the into the cavity, you typically construct a wall to a meter or meter and point two. And then once reinforcement is already in place, you pump the high slump concrete into place, it could be into these voids created by the hollow or it could be the cavity between two leaves that you are filling, where the reinforcement is also placed and this is something we have seen when we were looking at typologies of masonry construction.

So, you could either vertically fill the cavities in which the vertical reinforcement is sitting or you might have the U shape blocks, you can see a block which is cut in the shape of U for the horizontal reinforcement to run. So, you have both these possibilities, but it has to be high slump; because mind you, it is not a, it is typically not a very large cavity and you already put reinforcement there. So, you can have congestion quickly, because these voids are limited in dimension.

The cavity walls would primarily mean, you have placed the reinforcement in position, you have constructed the two leaves and you might need shuttering on the sides or depends on whether this wall construction that is continuing return walls that are continuing, and then you basically grout that cavity ok. So, this is how the construction with a grout is carried out and typically what the grout does is you have got a hollow cross section, you are grouting it with a significantly strong material, it is concrete strictly speaking. So, it increases the capacity, the strength capacity, the resistance, in shear, in flexure is immediately seen when you have grouted masonry. Primarily they are meant to hold the reinforcement in position right and give corrosion protection.

So, typical proportions you will have to take a decision depending on the available cavity, the size of the void that is available to you; whether you want to go with the fine grout or you want to go with the coarse grout. And depending on whether you are going the fine grout or a coarse grout, you actually will decide whether a fine, whether a coarse aggregate is going to be used or not.

Because if you have let us say, a void that is about 50 mm x 50 mm and you actually have a reinforcement bar sitting in there of say 14 mm or so, the space that you actually have is not too large. So, if you choose to go with coarse aggregate, you will have to ensure that the clear dimensions that you have are going to be pumpable spaces.

So, the choice between a coarse grout and a fine grout is something that is left to the designer. So, if you go with the coarse grout, you will go with you will choose a coarse aggregate as a part of the proportioning and if it is a fine grout, you do not use coarse aggregate.

Typical ratios are shown here, it could be different from these; 1:2, 1:3 is typically adopted, but an important point is that rarely would you go with a coarse aggregate size larger than 10 mm; 10 mm is the is a typical cap on the coarse aggregate dimension. Your question is whether load distribution would be changed. Strictly speaking if you look at a cross section, where you have the shell of the unit itself ok, you have the outer and the inner, inside of the structure and outside of the structure.

And then you have the core material which is now concrete, they are all of different. Let us say this is brick, this is clay brick, hollow clay brick and the core is concrete itself, the modulus of elasticity of these are going to be different right. So, at the cross section, the distributional stresses is going to be different because of different modulus moduli of elasticity- one.

The second problem is the unit is prefabricated and used. So, it is not going to change in shape or volume, where as the grout is pumped into the cavity, it will shrink; so when it shrinks, you could have issues of uniform transfer of loads and thereby you can have differences in stress distribution caused by shrinkage of the grout itself, ok.

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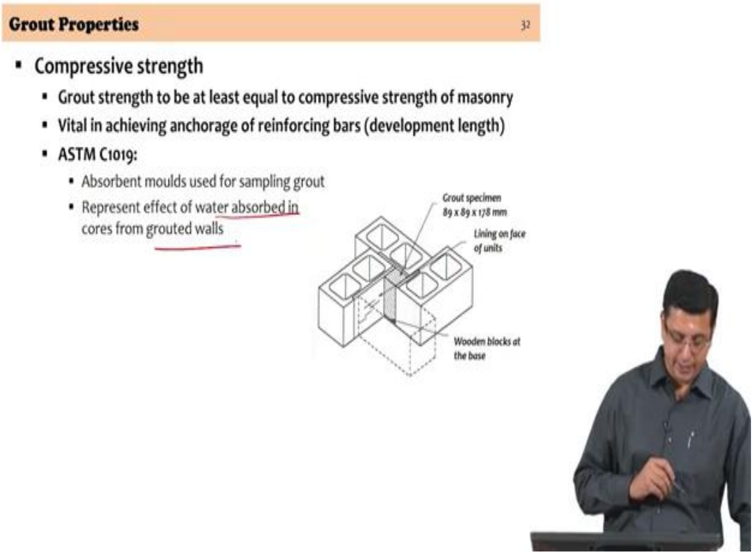

So, again since it is a property that can alter the strength of masonry, a check on the grout property, grout's compressive strength is one of the minimum tests that is carried out to characterize the grout itself. So, the grout compressive strength, we expect it to be at least equal to the compressive strength of the masonry, of the assembly right, it will work out to be close to the compressive strength of the masonry.

You basically cannot have very weak grouts, because it does not bode well for protection to corrosion of the steel reinforcement and after all the effort you do not want a grout that is weak and not contributing to the compressive strength of masonry. So, a good thumb rule is to see if your masonry compressive strength and the grout compressive strength are comparable.

Now, you should also understand that the reinforcing bars are sitting there, the reinforcement bars are going to be active in load transfer if the anchorages are good. So, the steel reinforcement is going to be depending on development on the grout, so you cannot have compromised strengths of the grout. So, this is something that requires due diligence in the mix proportioning and the quality of grouting itself.

So, for testing the compressive strength of the grout, we do not have any Indian standard that addresses the compressive strength testing of the grout, we depend on a ASTM standard and the ASTM standard referred to here as C1019 and it is an interesting test.

Now, since the grout is actually sitting inside the masonry unit or the concrete block, you are using a plastic high slump material which is going into something that has high water absorption; you have seen that clay brick can have good high water absorption, concrete also has water absorption. So, you actually pumping something plastic into this cavity, there will be water that is absorbed from the high slump grout by the units.

So, if you were to just take that high slump concrete and put it into a mould and go test the compressive strength of the mould, it will be completely wrong, because the water cement ratio in the high slump concrete when you are pumping it is much higher than what it is inside the cavity, because the walls will start absorbing the water in the grout. And what you would finally get, is possibly a stronger grout if there is the too much water is not absorbed.

So, the test protocol requires that you create a mould with real units that we going to be using in the wall construction. So, you can see how this arrangement is; you have got four blocks, you create a cavity and the size of this grout specimen is roughly 90 mm x 90 mm x 180 mm, I am sorry. Those strange numbers are simply because it is in inches that it is defined in the ASTM standards and conversion will give you these strange numbers, prismatic grout specimen.

And then what we do is that we actually place lining on the face of the units and this lining will not inhibit the absorption of water by the unit. So, you use something like blotting paper that is typically used to absorb moisture, you have to use something like that; can you tell me why you use that?

Student: Both the moisture.

No, you want the moisture to be absorbed, you want the moisture to be absorbed from the grout like in a real situation, but then you provide a lining material. Why do you provide lining material?

Student: There are no bond that is.

Exactly, otherwise if there is no lining material, the grout will actually bond with the units and you cannot do any test there. So, you give a lining material, but ensure that this lining material is not going to prevent absorption of absorption of moisture. So, it is an absorptive lining material that is provided and at the bottom you normally give a wooden block, so that you get a finished surface. And then once it is hardened, you move away the blocks, use this, test it in compression and that gives you the grout compressive strength, so that is how this test is conducted.

You have to basically create the absorbent mould. So, you will be careful about what material you choose to create the absorbent mould such that you represent the effect of water that the walls actually will absorb from the high slump grout ok; so that is the grout compressive strength.

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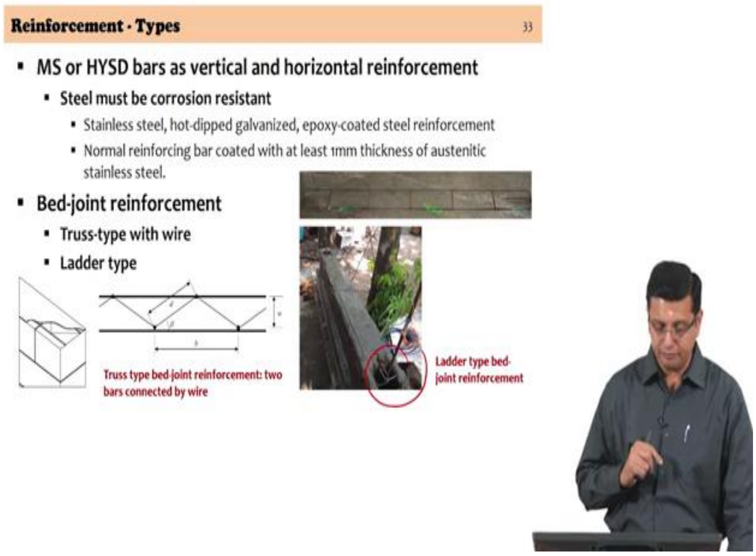

Of course, if you are using a clay brick, hollow clay brick or any other type of block, you have to be sure that you are using a similar material to create the grout sample, grout specimen to replicate the typical absorption that you get in such a material The fourth component- unit, mortar, grout, reinforcement, a steel you can test it, like you would test reinforcement steel for concrete and you need to know these strengths if you are designing your masonry.

Typically, mild steel or high yield strength, deformable steel are used both for vertical reinforcement and horizontal reinforcement. So, a standard tension test is done to estimate the tensile strengths of these materials. It is recommended, strongly recommended that corrosion resistant steel or procedures to ensure corrosion resistance is put in place for steel, because unlike in concrete where you have good corrosion protection by design, by the composition of concrete itself. In masonry that is the big challenge, because masonry units are porous.

So, you can do different things, the IS code, the national building code recommends that you use you use stainless steel, because stainless steel is not completely corrosion resistant, stainless steel is not corrosion free, but it takes a longer time for stainless steel to corrode, you could use rods that a hot-dipped galvanized or epoxy-coated steel reinforcement for the construction.

There is a trend to use epoxy bars, there is a tendency to use carbon fiber reinforced or FRP bars for construction. This is something that is still in a research R and D stage, because there are issues of bond and also economics, the cost of these of this type of construction which matters, but if in the future FRP bars going to become easily available and solves completely all the other problems in the construction of the structural material, I think you overcome corrosion as far as structural systems like these are concerned.

There is another possibility that you could use normal reinforcing bars, but which have a coating of stainless steel around at least for a millimeter. And therefore, you have to be careful that you are using corrosion resistant steel and you cannot complain that masonry has led, reinforcing masonry, has led to severe corrosion problems. This is mentioned to you, well in advance by the codes themselves.

Let us say you have a bed-joint and you place a reinforcement bar, and give cover of 15 mm above and below, then you will get a very thick mortar joint in relation to the unit itself, this ratio is a critical ratio and there is a direct correlation between the thickness of the mortar joint and the strength of the masonry itself; so thinner the mortar joints, stronger is the masonry. So, you have again a conflicting requirement here, steel has to be protected, but you need thin mortar joints.

So, if you remember in the typologies of masonry, I was talking about high strength bed-joint mortars. The whole idea of high strength bed-joint mortars is to ensure that you get thin bed-joints, when you have steel in the in the joint itself. So, bed-joint reinforcement;

you have couple of good options for bed-joint reinforcement, today available in the market.

One of them is the truss type, it is in the form of a truss and the inclined elements are either made out of thinner cross section of bars or even strong wire. Now, this the trusts type reinforcement with the wire actually ensures that the percentage of steel is achievable, but you can reduce the size of the steel bars and thereby you can minimize the joint thickness itself. So, it is a good; it is a good typology and there are different ways in which these wires are attached- some of them are welded, but welding very thin, elements in steel has other complication. So, this is another area by itself.

You can also have this ladder type joint reinforcement bed-joint reinforcement, which is basically with the series of lugs between the rods again. This is again a typology that will help you achieve a certain percentage of steel that you require for the joint itself and minimize the size of the reinforcement as much as you can.

Of course, the bed-joint reinforcement has to be coupled with the vertical reinforcement and that is the kind of detailing that you are seeing here, where vertical reinforcement is connected to the horizontal reinforcement as you have seen, the horizontal reinforcement improves the effectiveness of the vertical reinforcement in flexural capacity itself, ok.

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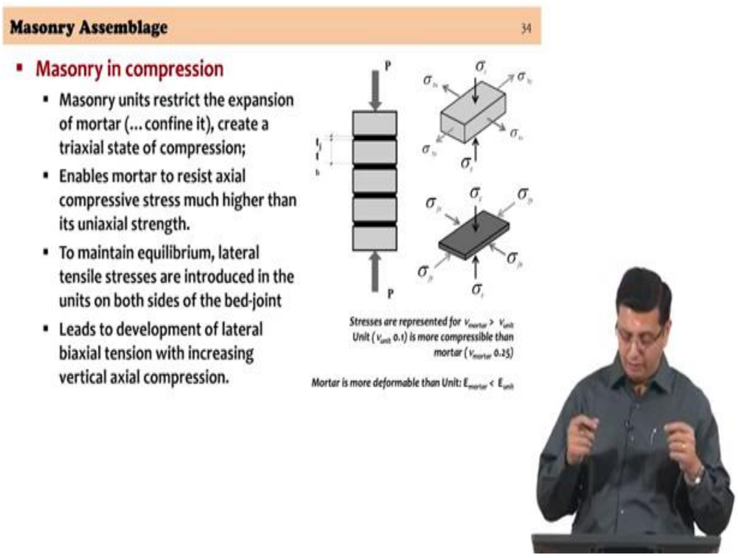

So, having examined the different components of masonry construction, four of them. We now start looking at the masonry assembly itself and properties of the masonry assembly, strength properties, primarily compressive strength, tensile strength, but here we are examining the flexural tensile strength. And we will examine flexural tensile strength parallel to the bed-joints and perpendicular to the bed-joints, and then the shear strength of masonry. These are characteristics, these are mechanical parameters that directly impact the strength of the masonry.

So, to begin with, we will examine behavior under compression and how it is tested for compression, and what factors influence the compressive strength of masonry itself. So, if you take a stack of bricks subjected to uniaxial compression, the behavior in the assembly - There are three different materials or interfaces in this assembly; the first one being the unit, the second one being the mortar and the third- it is plain brick masonry, there is no reinforcement. The most critical is the interface between the mortar and the units and that has a completely different stress strain behavior compared to the unit and the mortar. So, it is really these three working together under compression, right.

And you will start getting used to the fact that we are going to be talking about the behavior of the unit, the behavior of the mortar and how is the interface, how is this unit-mortar interface behaving under every action. And the complexity of masonry is to be able to establish the behavior under compression, the behavior under shear, the behavior under flexure, you have to break it down to the individual behavior, individual load-displacement behavior.

But then of course, to complicate our life it is not additive, if you add all this, you will not get the behavior of the masonry. So, it brings in complexities it is closer to anisotropy than isotropy for sure, not even orthotropic. So, we will examine the effect of this interface in the behavior first under compression, but we will be examining this under the other actions as well, ok.

So, what happens? You look at a masonry construction, you have the unit and the mortar, these are you know lined up, stacked up. The masonry unit; masonry unit which is less deformable right; it is more brittle, it is less deformable; actually starts confining the mortar, because of mortar is more deformable of the two constituents. The mortar tends to expand, it is not in the plastic state that we talking about, the plastic state of course, it gets squeezed out of the joint, but even when it is hardened and you keep loading the masonry, the mortar tends to expand more than the unit.

So, but since a bond is present between the unit and the mortar, the unit starts confining the mortar, so there is what is referred to as a co-action between the unit and the mortar. Because of which, because the units starts confining the mortar, the mortar is in a state of triaxial compression, vertically you have the gravity load, but in the other two lateral directions, the units starts confining the mortar.

So, if you look at the state of stress in the mortar, it is in triaxial compression, it is completely confined. Your question is whether this confinement is coming from the unit above and below in a stack or from the neighboring units in a wall construction ok. As of now we are actually examining the stack and the confinement is because of the bond with the unit above and the unit below.

We are not talking of the kind of confinement; actually while the confinement from neighboring adjacent units in a wall constructed in a certain pattern exists, this is more critical right. So, the mortar is an state of triaxial compression.

Now, it is important to pause for a moment and an understand what is really happening. You can go and estimate in the cube compressive strength of the mortar, you are able to estimate the uniaxial compressive strength of mortar right. In the lab test you actually just doing uniaxial compressive strength, but in reality, the mortar in the wall construction is not under uniaxial compression, it is under triaxial compression ok.

So, how do you get the triaxial compressive strength of the mortar or how would you estimate the compressive strength of the masonry by just having the knowledge of the uniaxial compressive strength of the mortar? So, this is the trick in the behavior of masonry and is something that is addressed. In the next module, you will see how the uniaxial strength of mortar, then find its way into an estimate of the compressive strength of the masonry with necessary modifications to account for the confinement effect or the state of triaxial compression.

Now, the bond exists, the mortar has a bond with the unit above and the unit below because of which as the mortar is getting confined, the unit in turn experiences tension because of the bond, right, equal and opposite actions. So, as I said the mortar is now resisting, is expected to resist higher compressive strength because it is in a confined state than the uniaxial compressive strength of the mortar itself. So, this is a point you need to keep in mind.

Because of the bond and because of equilibrium, the unit now starts experiencing tensile stresses ok. So, if you look at the triaxial state of stresses in the unit, vertically in the gravity direction this compression. So, there is vertical compression, but in the two lateral directions because the mortar is deforming in both directions, it is free to deform in both directions you have bilateral, biaxial tension in the unit, ok. Now, that is a catch because unit is the brittle material of the two and could be weak in tension. So, this mechanism is what causes the formation of cracks in the unit at failure, ok.

So, this co-action is something that is at the foundation of how masonry is going to behave. However, a word of caution, this is true; this understanding of triaxial compression in the masonry mortar and the biaxial tension and uniaxial compression in the unit is true as long as Poisson's ratio of the mortar higher than the Poisson's ratio of the unit meaning this unit is more compressible than the mortar. This theory is valid as long as your compressibility of the unit is more than the compressibility of mortar.

So, typical values if you want to look at the Poisson's ratio of the unit would be of the order of 0.1, and the Poisson's ratio of mortar would be about 0.25 or higher. So, the unit is more compressible than the mortar, this should not be confused with the deformability. The as far as deformability is concerned and we are examining properties such as the modulus of elasticity, the modulus of elasticity of mortar is higher than the modulus of elasticity of unit.

So, in terms of deformability, softer material, mortar is a softer material; unit is the harder material, and more brittle material. But as far as compressibility is concerned, you know that material like cork is more compressible right. And it has it has a Poisson's ratio close to 0 unit is about 0.1. Rubber is highly incompressible about 0.5 and the mortar is at about 0.25. So, it is the compressibility that matters as far as the problem on hand is concerned.

And because of the mortar being less compressible, it gets into the state of triaxial compression at the bond, ok. So, and you need to keep this in mind because if the composition of the unit in the mortar such that you get mortar is going to be more compressible than the unit, you can have a completely different way in which the stresses are going to be working out for you in the failure of the masonry in compression.

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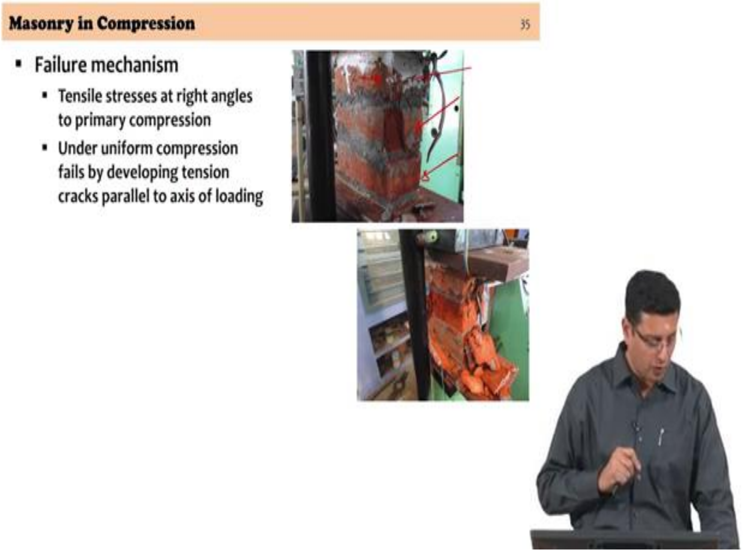

So, we will examine that it is very well documented in the literature. So, as far as failure is concerned, these tensile stresses developing in the unit in the lateral directions will actually lead to formation of vertical cracks in the unit, and that is how the unit will fail ok. The moment the unit fails the confinement to the mortar at that joint is lost. So, the mortar now suddenly falls from a state of triaxial compression, confined compression to a state of uniaxial compression, its compression strength suddenly drops and it gets crushed. At the same value which was able to resists suddenly fails under the same value, because it has now shifted from triaxial confined compression to uniaxial compression state.

So, you see the formation of these fine vertical cracks. I hope you are able to observe these cracks. You will not see single cracks, but you will see a series of you will see a series of fine vertical or sub vertical cracks like you would see in a concrete cylinder on or concrete cube, these series of sub vertical cracks form, these vertical cracks are going to be the unit. And once they sufficiently form you will get you will get bulging and failure in the unit itself. So, these cracks are all going to be parallel to the direction of loading and at ultimate you would see a crushed system the mortar would actually be powder.

And in this state, if you go and pull out the mortar, it is actually powder because the unit has failed, and it is not offering anymore confinement and you will see that the mortar is also crushed at this at this point of the test itself.

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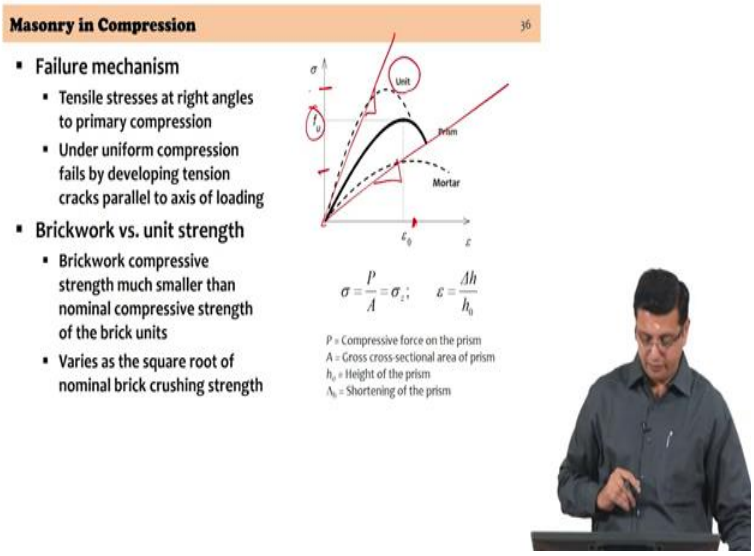

Now, it is important to understand the behaviour of the strength of the brick work, when I say brickwork is the assembly versus the strength of the unit itself right. And when you actually look at the stress-strain curve of the unit and the stress-strain curve of mortar, this is where we said, unit is stronger right; unit is stronger, but less deformable, modulus of elasticity of the unit versus the modulus of elasticity of the mortar. So, the mortar is more deformable, but of lower strength. Together, they give you something that is in between as far as the masonry is concerned.

So, if you were to compare the strength of the brickwork masonry versus the strength of the unit itself, the brickwork compressive strength, masonry compressive strength is lower than the unit compressive strength ok. And typically, the correlation between the two, the relation between the two is that the brickwork compressive strength, the masonry compressive strength varies as the square root of the compressive strength of the unit or the crushing strength of the unit. This is typically observed relationship between the masonry compressive strength and the unit compressive strength, that it varies as the square root of the crushing strength of the unit itself.

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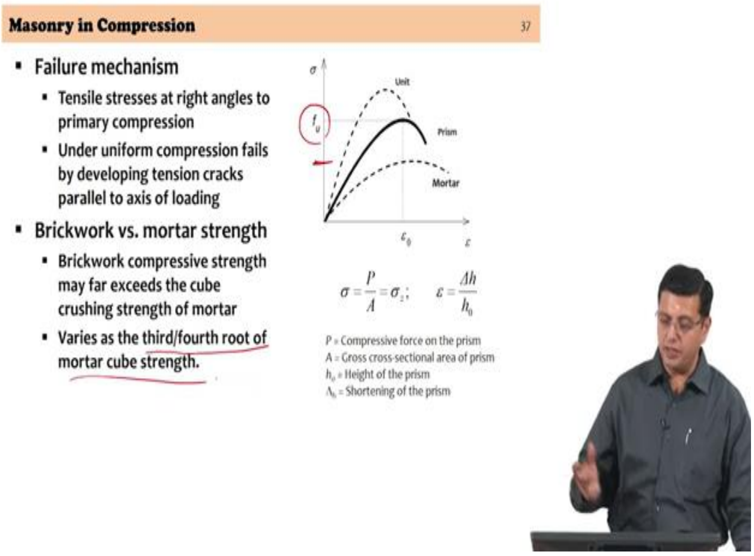

But if you were to examine the mortar, the mortar, the strength of the mortar in the masonry will be higher because of the triaxial confinement, the triaxial compressive stress in the state of confinement and will have a value, the compressive strength of the masonry will be significantly higher than the strength of the mortar itself. And this is because of the triaxial effect that is there the triaxial confinement that is there of the mortar.

And the way the mortar compressive strength and the prism strength or the masonry strength are related is in this manner that the brickwork compressive strength, masonry compressive strength varies as the third or the fourth root there is variability depending on the compositions, third or the fourth root of the mortar cube strength. So, this is how you would be able to relate the constituent strength to the strength of the assembly itself.

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So, just to summarize the inferences on the compression failure in masonry, the uniaxial compression and the bilateral tension that is forming. These are the these are secondary tensile stresses because of Poisson's effect that is developing in the unit itself. These are lateral actions; the lateral bulging is causing these stresses, because you have the bond, it does not allow it to bulge and lateral tension, secondary tensile stresses is causing the splitting of the brickwork.

The compressive strength of the unit, therefore, is really not a direct measure of the compressive strength of the masonry and that is simply because it is controlled by the mortar. It depends on the strength, the compressibility of the mortar, the failure of the unit in compression individually is different from the failure of the unit in the masonry assembly.

So, if you have a very strong brick unit, it does not mean that you will get strong masonry, it depends on what the mortar is going to be. So, the basic message is, you cannot qualify the properties of the masonry by simply doing a test on the unit. If you have good quality unit it does not mean that you got good quality masonry. You have to be very careful about that you have to have a measure of the compressive strength of the masonry itself.

The mortar instead withstands higher compressive stresses in the brick work because of the multi axial state of stress. So, we will stop here and we will look at what happens if you have different materials in the mortar joint, does it give us an insight into the structural mechanics of the masonry itself.