PLASTIC SHRINKAGE CRACKS ANALYZED FROM A DIFFERENT PERSPECTIVE

DHRUBJYOTI BHATTACHARYA[1] AMITABHA DATTA[2]

ABSTRACT

Cracks in green concrete are very common phenomenon and it is observed on surface of concrete very often. In fact these types of cracks, of shallow depth, owing to dehydration, are called as "Plastic Shrinkage Cracks" or conventionally "Surface Shrinkage Crack".

During Plastic Shrinkage in concrete, formation of cracks of 'shallow depth' is not the only category; Plastic Shrinkage Cracks may also occur of 'deep depth' in concrete. Discussions in this paper are mainly on this "Plastic Shrinkage Crack" of two categories.

"Plastic Shrinkage Cracks" occurs only prior to hardening of concrete, that is, generally shrinkage cracks form in concrete at its plastic state that is in Green stage, only. Plastic Shrinkage cracks are very commonly known as 'Surface Shrinkage Cracks of shallow depth'. It is true that major percentage of surface cracks is limited to surface of the concrete only. While, concrete in roof slab or deck slab, where depth of concrete are not much, probability of formation of crack shall also be of shallow in depth.

Besides these "surface crack", plastic shrinkage may create even deep cracks owing to excess bleeding in concrete. If the concrete is for large and bigger depth RCC Structure, the simple surface shrinkage cracks, as expressed above, may occur on the top surface. But probability of deep crack formation also remains in concrete in the last layer of pour (of concrete) depth, which may even be up to one meter from top. This deep Plastic Shrinkage crack is non-conventional, but it occurs in certain cases at site.

Mainly based on the said two categories of Plastic Shrinkage Cracks, discussions have been made in this Paper. Identifications of the cracks, its nature and consequently its effect on the structure are the main subject of this Paper. Comparison of the plastic shrinkage cracks of the two categories is also stated herein later to avoid any confusions, so that identification of the specific crack becomes convenient.

1. INTRODUCTION

Crack in concrete can be defined as an effect on concrete due to failure of 'Tensile Strength' in concrete. Our discussions are on Concrete at Plastic Stage; Not at Hardened Stage.

Formation of cracks in Green–stage concrete that is in Plastic stage–concrete (prior to hardening) occurs due to mainly-

i. Plastic shrinkage Cracks (Cause: Shrinkage in concrete by the effect of dehydration owing to adverse weather condition or inadequate curing)
ii. Plastic settlement Crack(Cause: subsidence of concrete mass by the effect of dehydration)
iii. Restrain to movement during hardening stage
iv. Differential Settlement of base support
v. Sub-grade movement

Besides, some more different cracks in plastic concrete may arise during construction due to inadequate design or incorrect construction procedure.

Taking into account the focus of the subject of this Paper, detailed discussions on the other issues except "Plastic Shrinkage Cracks" are avoided. "Plastic Shrinkage Cracks" and "Plastic Settlement Cracks", being very similar, a brief definition/concept of "Plastic Settlement Cracks" shall be described hereafter to avoid any confusion.

1 Senior Bridge & Foundation Engineer, E-mail: dhruba48@gmail.com
2 Chief – International Operations (Ex Vice President), E-mail: damitabha2005@gmail.com
} STUP Consultants Pvt. Ltd., Kolkata

Owing to dehydration in concrete at plastic stage by the effect of weather, inadequate curing or/and excess bleeding due to over vibration in concrete, shrinkage occurs that is, reduction in concrete volume develops. Volume reduction in concrete causes movement in concrete ingredients.

Depending on the depth of the last layer of concrete (last layer of pour) and consequently due to vibration, movement in concrete ingredients occurs resulting cracks and its type and depth.

If the affected depth of the last layer of concrete is shallow, restricted movement in concrete ingredients may not create substantial segregation and failure of tensile strength will not affect the concrete badly. Depth of such cracks shall generally be small and limited within the cover zone.

If the affected depth of last layer of concrete is high, movement in concrete ingredients may create segregation upto the full affected zone and in effect, the cracks may form deeper.

While the last layer of concrete is of shallow depth, restriction of space confines the segregation, whereas, for the higher depth of last layer of concrete, segregation effect reaches upto the bottom of the affected concrete.

The weakened tensile strength of the green concrete, owing to weak cohesive force due to dehydration, cannot resist the tensile stress being developed due to the said movement of the concrete.

Thus Deep Plastic Shrinkage Cracks are formed in bigger depth concrete and shallow cracks in shallow depth of concrete.

Plastic Shrinkage sometimes develop deep cracks in the last layer of concrete pour (while layer depth of concrete is big), owing to excess bleeding. These deep cracks are not very much common.

Thickness of deck slabs or roof slabs are generally lower (generally 200 mm to 300 mm), so question of excess bleeding in concrete does not arise, unless the concrete contains excess water, to making high slump.

Deep crack formation, owing to excess bleeding occurs in RCC Structures, where the last layer of pouring of concrete is substantially high.

Such "Plastic Shrinkage Deep Cracks" are very much uncommon.

Site engineers are not much aware of such deep cracks, caused owing to mainly excess bleeding.

This paper is mainly prepared in view of making clear differentiation between the two categories of plastic shrinkage cracks

i. One of shallow depth and
ii. Second of deeper depth.

We shall further discuss these two types of cracks in brief with requisite analysis.

While it is confirmed that cracks formed at site are neither due to plastic settlement nor due to differential settlement of base supports or due to fault of design, the final decision is to take on plastic shrinkage crack – whether the crack is deep or on surface only.

Our discussions in this paper shall mainly be limited to Plastic Shrinkage Cracks only, for the said two categories. Comparison will be drawn for clear identification and conception.

2. CONCEPT OF PLASTIC SETTLEMENT AND PLASTIC SHRINKAGE IN GREEN/PLASTICCONCRETE AND SUBSEQUENT DEVELOPMENT OF CRACKS.

All the Plastic Settlements as well as Plastic Shrinkage cracks are formed while the concrete remains in Green Condition (Plastic State). Such green concrete tenure is till the initial setting time of the concrete.

All the concrete, while in plastic condition, get cohesion bond amongst the ingredients of concrete with the help of water, cement and finer materials by the effect of surface tension (i.e., capillary action) and chemical reactions with cement and water.

If water gets out or taken out of the concrete by any means (by physical or by mechanical means) dehydration occurs.

Dehydration is the prime factor behind both Plastic Settlement and Plastic shrinkage. But based on the depth of the concrete structures and the depth of the last layer of concrete poured, the basic types of dehydration may vary.

i. In case of shallow depth concrete, such dehydration occurs (at concrete top surface) due to adverse weather and or inadequate curing.

ii. In case of deep depth concrete, such dehydration occurs (at concrete top surface) due to excess bleeding against excess vibration in the last layer of concrete pour of high depth.

Dehydration occurs on top concrete surface by the effect of adverse weather or inadequate curing. Dehydration also may occur due to excess bleeding in concrete caused by excess vibration. Even both the drying operations may occur at a time on the concrete.

Due to dehydration, volume of Concrete will reduce; movement in concrete mass occurs due to shrinkage or segregation. Concrete will lose its bond amongst ingredients either partly or fully, due to failure in tensile strength. Thus having inadequate bond or cohesion amongst the ingredients of concrete, "Plastic Settlement" in concrete as well as "Plastic Shrinkage" in concrete may occur.

2.1 Plastic Settlement in concrete and Development of Cracks

For normal or partial loss of tensile stress, concrete may shrink as well as subside to certain extent, due to reduction

in volume. In the effect of such subsidence of green concrete, due to obstruction by top reinforcements bars or bigger aggregates, some cracks may be visible along the top reinforcements (particularly when cover depth is less) as well as at some localized zone on top surface of the concrete (due to obstruction by stones). These cracks are called "Plastic Settlement Cracks".

2.2 Vital Causes of formation of Plastic Settlement Cracks

Major cause of Plastic Settlement Cracks is reduction in the volume of concrete due to dehydration of concrete in the effect of adverse weather condition or inadequate or non-curing as well as bleeding and subsequent segregation. Further causes are:

i. Internal obstructions due to reinforcement steel or large size aggregate
ii. External restraining due to relatively narrow formwork
iii. Radical change of concrete cross section
iv. Absorbent sub base or formwork surface
v. Flared column heads
vi. Bulging or settlement of formwork and supporting system

Besides the above, the following aspects are the vital criteria for such Plastic Settlement Cracks.

2.2.1 Primary aspects:

i. Non-cohesive concrete mix
ii. Excess bleeding
iii. Over vibration

2.2.2 Secondary aspects:

i. Rapid Early Drying Conditions
   (a) High ambient temperatures/Hot Sunny weather
   (b) Low Humidity
   (c) High Wind velocity

Plastic Settlement may occur in shallow as well as deep depth of concrete structures, but the last pour of concrete shall generally be of shallow depth.

Sometimes this Plastic Settlement Cracks resembles to the Plastic Shrinkage Cracks. To avoid any confusion, the concept of "Plastic Settlement" is required to be well

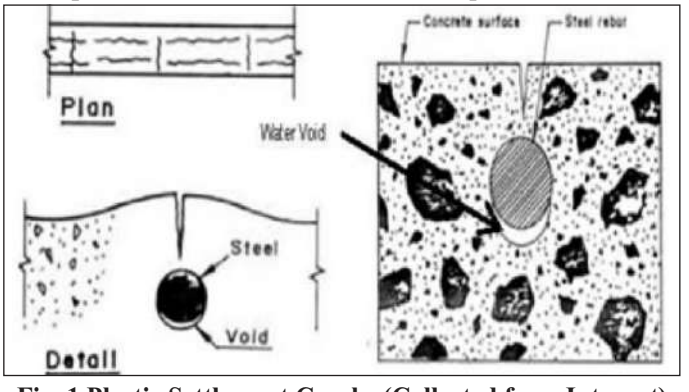

Fig. 1 Plastic Settlement Cracks (Collected from Internet)

In summary, this "Plastic Settlement" is subsidence of the total agitated (owing to vibration) green (plastic) concrete mass of the last layer concrete poured. During subsidence of the concrete, cohesion bond (tensile strength) of the concrete is partially (not fully) lost due to dehydration. As well as, in concrete no substantial segregation occurs. No excess bleeding (limited to 5%) occurs. Dehydration and development of consequent subsidence is owing to adverse weather and/or bleeding (normal) of concrete. By the effect of obstruction during subsidence of concrete by reinforcement steel bars or any other materials, cracks may develop on concrete surface.

2.3 Plastic Shrinkage of shallow depth and development of Cracks in Concrete

Shrinkage of concrete in the last layer (shallow depth) of concrete poured, causes movement in concrete ingredients upto that shallow depth. This movement, owing to shrinkage, develops tensile stress. This tensile stress could not be sustained due to failure of week tensile strength (caused owing to failure of cohesion force in dehydrated cement paste). This failure of tensile stress causes formation of Cracks. These cracks may form on any concrete top surface.

As the last poured concrete is of shallow depth, shrinkage and segregation thereof (if any) in concrete cannot aggravate due to lack of adequate space. Shrinkage and subsequent movement of concrete ingredients on top zone forms cracks. These cracks are called "Plastic Shrinkage Cracks of shallow depth". These cracks are also called "Surface Shrinkage Cracks"

Fig. 2 Plastic Shrinkage Cracks of Shallow Depth

2.4 Plastic Shrinkage of Deep Depth And Development of Cracks in Concrete.

Segregation of concrete in the last layer of concrete poured, is developed due to excess vibration and bleeding thereof. Subsequently dehydration and reduction in concrete volume occurs. Reduction in concrete volume causes movement in concrete ingredients. This movement in concrete continues up to the vibrated depth (last poured) of concrete.

While the last layer of poured concrete is of deep depth, "Plastic Shrinkage Cracks of deep depth" may develop in this deep layer of last poured concrete due to segregation and subsequent movement of concrete ingredients.

Fig. 3 Plastic Shrinkage Cracks of Deep Depth

It is to be noted that formation of such deep depth plastic shrinkage cracks occurs owing to certain common construction flaws.

While RCC structure is reasonably high in depth (more than one meter deep).

- Thickness of last poured concrete layer is more than 600 mm and sometimes even around 1,000 mm.
- Excess vibration in concrete was applied in last poured concrete layer for full depth of the layer.
- Owing to excess vibration, excess bleeding in concrete occurs and cement slurry seizes out from concrete top surface.
- Seized out cement slurry, due to bleeding, while thrown outside from concrete top surface or dry cement or cement-sand mortar while spread over the cement slurry for finishing purpose.

Obviously, the aforesaid construction flaws are not natural phenomenon and not within acceptable criteria. But it happens in cases of the Projects.

Whereas no specific restriction is applicable for conventional Plastic Shrinkage Cracks of shallow depth, that is Surface Cracks, which occurs at the concrete top surface during its green stage only. This surface shrinkage cracks may occur on any concrete top surface.

The basic technology of formation of deep cracks in deep depth concrete structures is similarly the effect of 'dehydration' in concrete. Such concrete dehydration occurs on top surface of deep depth concrete structures owing to mainly excess bleeding.

Dehydration causes reduction of water from concrete and in effect, the volume of concrete gets reduced.

Due to reduction of volume owing to dehydration, by the effect of excess bleeding, the concrete mass will have movement amongst the ingredients and subsequently failure of tensile strength may cause segregation.

The weakened tensile strength of the green concrete, owing to weak cohesion force due to dehydration, cannot resist the tensile stress being developed due to the said movement of the concrete.

Ingredients of concrete of Higher Specific Gravity will move down and ingredients of lower Specific Gravity shall move upward (caused by capillary action) by the effect of segregation, which results up and down movements amongst the green concrete ingredients and develop Tensile Stress.

The failure of tensile stress causes formation of "Plastic Shrinkage Cracks of deep depth".

2.5 Plastic Shrinkage Cracks occur only in the zone of Top (last) Layer of Concrete pour.

It has been noted hereinbefore that both "Plastic Settlement Cracks" and "Plastic Shrinkage Cracks", are the occurrences in the top layer of poured concrete.

Owing to dehydration i.e., dryness, volume of plastic concrete reduces due to shrinkage and or segregation.

Effect of such dehydration will act mainly in the zone of Top (last) Layer of Concrete pour. Cracks are developed in that last layer of concrete zone only.

2.6 Nature of Cracks

Formation of cracks and depth of it in concrete depends on movements of the concrete ingredients. Cracks develop in this agitated zone only.

2.7 Cracks are Wider at outer Face and Fine at the Inner end of the Crack

Dehydration commences from concrete top; Reduction in volume also commences from top; Shrinkage in concrete or segregation in concrete similarly starts from top of concrete only. Therefore, maximum effect on crack formation is at top surface of concrete and minimum at the down most inner point of movement in concrete ingredients. As a result the cracks are wider at top with respect to the lower portion.

"De-hydration" is the major and prime factor for developing of cracks in plastic concrete.

During generation of cracks, owing to dehydration, generally the following nature of formations of cracks is followed:

i. From top concrete surface to inner concrete.
ii. From vertical concrete face to inner concrete.
iii. As a result maximum gaps in cracks of concrete develop at concrete edge (edge of vertical & horizontal faces), because this concrete edge is having two outer ends free.

iv. It is why the nature of such cracks become converging from edge.

Dehydration and subsequent movement in concrete ingredients occur in almost up to the total depth of the last layer of concrete and depth of cracks reaches up to the depth of agitation in concrete.

2.8 Bleeding in Concrete

Bleeding in concrete is a very common phenomenon during execution. During agitation in concrete by the effect of vibration, water, having lower specific gravity as compared to other ingredients of concrete, tends to rise up to top due to capillary effect.

Water cement ratio is one of the major factors which control the rate of bleeding. Other factors are ratio of coarse aggregates to fine aggregates as well as use of finer materials like fly-ash and additives like admixtures etc.

Bleeding in concrete is generated, mainly when the concrete is in plastic condition (green) and agitated by any outer means like vibrators etc.

Reasons for which water of concrete comes out:

i. Absorbent sub-base or absorbent form work.
ii. High w/c ratio in concrete mix.
iii. Less fine aggregates (sand) in concrete mix design.
iv. Over vibration in concrete.
v. Over tamping of the concrete top surface for leveling purpose.
vi. Leakage of cement slurry during concreting and or vibrating.

The process of coming out of water (with finer materials) is BLEEDING.

2.8.1 Normal bleeding

Normal Bleeding is defined up to 5%. Refer Table 1A of IS 9103:1999. Effect of normal bleeding is not harmful; this may even improve the quality of concrete due to optimization of '*w/c'* ratio. In any case, 10% or more bleeding may be considered harmful as it may cause deep cracks in concrete owing to failure of tensile strength of concrete. Besides, reduction in water/cement (w/c) ratio may be the prime cause of deterioration of concrete strength.

While rate of 'concrete-surface evaporation' is less than 'Normal Bleeding' it gives protection against surface dehydration and subsequently probability of surface shrinkage cracks reduces.

2.8.2 Excess bleeding and its effect

The Bleeding, when it is more than 5%, is defined as Excess Bleeding. Excess Bleeding, as such, has no positive effect on concrete. Adverse effects, in brief, are as under:

Develop dehydration; Dries up; Causes reduction in Concrete Volume; Causes failure in tensile strength (cohesion bond);Creates movement in ingredients of concrete mass; creates segregation of concrete and subsequently develops formation of crack.

2.8.3 Excess bleeding causes damages to the concrete as below

i. Lack of homogeneity in concrete.
ii. Segregation in concrete.
iii. Dehydration of concrete results "plastic shrinkage crack".
iv. Dehydration, owing to bleeding in concrete, affects the quality of concrete.
v. Excess permeability in concrete.
vi. Excess bleeding may form water accumulation/ entrapped water (water voids) in concrete, which deteriorates the bond with aggregate and cement paste in concrete.

2.8.4 Method of measurement of bleeding

Bleeding of concrete is generally measured in percentage of the total mixing water in the sample. Bleeding shall be computed at a percentage of the net amount of mixing water in the concrete.

Refer Clause 7.2.4 of IS 9103-1999 and its ANNEX – D in this context.

Sometimes it also measured as volume of bleed water of concrete per unit area of concrete top surface.
Refer Clause 7 of ASTM: C 232-99.

3. COMPARISON AMONGST THE CATAGORIES OF PLASTIC SHRINKAGE CRACKS OF SHALLOW AND OF DEEP DEPTH.

The standard comparisons on categories of Plastic Shrinkage Cracks are placed hereunder, which will even express an overall concept on the subject, discussed herein above.

Table 1 Comparison Amongst the Catagories of Plastic Shrinkage Cracks of Shallow and of Deep Depth.

Sl. No.	Subject Matter	Plastic Shrinkage Cracks of Shallow Depth	Plastic Shrinkage Cracks of Deep Depth.
1	Concrete Stage	Plastic (Green) Stage of Concrete	Plastic (Green) Stage of Concrete
2	Type of RCC Structure	Any RCC Structure; Specially Roof slab, Deck slab etc.	RCC Structure having higher depth, generally more than 1 Meter.

3	Zone of Crack	Last layer of pour of concrete Normally Layer depth ≤ 300 mm	Last layer of pour of concrete Normally Layer depth >300 mm. Sometimes layer depth is more than 600 mm even around 1,000 mm.
4	Prime Factor of Formation of CRACK	Dehydration Effected by adverse hot weather and inadequate curing.	Dehydration Effected by adverse hot weather and inadequate curing as well as Excess Bleeding due to over vibration.
5	Shrinkage in concrete volume	Shrinkage in concrete volume in the last layer (shallow) of pour of concrete due to dehydration. Effected mainly by: Hot weather and inadequate curing.	Shrinkage in concrete volume in the last layer (deep) of pour of concrete due to dehydration. Effected mainly by: Excess bleeding.
6	Bleeding in Concrete	Normal Bleeding (5%) occurs. Excess Bleeding in shallow depth normally does not occur, unless additional water is added to concrete mix for increase of slump.	The last concrete pouring depth being high, probability of over vibration remains and such over vibration creates Excess Bleeding in concrete.
7	Segregation in Concrete ingredients	Owing to shallow depth of concrete last layer, vibratory agitations in concrete are less and bleeding also remains restricted. So probability of excess bleeding does not arise. Thus segregation in concrete ingredients is very much restricted and insignificant within the agitated zone.	Owing to high depth of the last layer (pour) of concrete, probability of over vibration remains in concrete and thus extensive segregation amongst the ingredients may occur due to excess bleeding.
8	Movement in Concrete ingredients	Owing to shrinkage in concrete mass and effect (minor) of segregation in concrete, movement in concrete ingredients becomes effective.	Owing to substantial reduction (shrinkage) in concrete volume and effect of extensive segregation in concrete, significant movement in concrete ingredients becomes effective.
9	Formation of Plastic Shrinkage Cracks	Segregation of concrete is insignificant owing its shallow depth. Mainly the dehydration vis-à-vis shrinkage phenomenon creates movement in the concrete mass. The weakened tensile strength of the green concrete, owing to weak cohesion force due to dehydration, cannot resist the tensile stress being developed due to the said movement of the concrete. This phenomenon of failure of tensile strength in concrete ultimately results to crack.	Segregation in concrete in the deep depth of last layer of concrete pour can make substantial movement in the mass-concrete. As well as, surface dehydration vis-à-vis surface shrinkage phenomenon also aggravate segregation and consequently movement in the concrete mass. The weakened tensile strength of the green concrete, owing to weak cohesion force due to dehydration, cannot resist the tensile stress being developed due to the said movement in the concrete. This phenomenon of failure of tensile strength in concrete ultimately results to crack.

10	Depth of Cracks	Movement of concrete ingredients shall be limited to the zone of concrete, poured in the last layer (of shallow depth) and depth of crack shall accordingly be limited to that shallow depth of concrete.	Movement of concrete ingredients shall be limited to the zone of concrete, poured in the last layer (of deep depth) and depth of crack shall accordingly be limited to that deep depth of concrete.
11	Whether the cracks are detrimental to the RCC structure and action of repair.	Plastic Shrinkage Cracks (Surface cracks) of shallow depth are not detrimental to the structures. The surface cracks are required to be repaired to avoid future corrosion on reinforcement bars.	Plastic Shrinkage Cracks of deep depth may cause harm to the structures. The cracks may be inspected thoroughly; concrete core crushing strength may be checked. Based on such detailed inspections, method of repair is judged.

4. PRECAUTIONS TO AVOID CRACKS, PARTICULARLY DEEP CRACKS

Some most important precautions are briefed hereunder, which may help the young site Engineers to avoid the cracks or minimize the cracks during construction of RCC structures.

i. To restrict the depth of each pour of concrete to 300mm to 400mm and the last layer of pour strictly to 300mm or less.
ii. Never to add additional plasticizer or water to green concrete directly for convenience and to have high workability of concrete.
iii. Strictly there should be no leakage in form works to control bleeding.
iv. Base of concrete & Shutters shall be non-absorbent.
v. Vibration in concrete must be optimum to get consistent and homogeneous concrete. Over vibration should strictly be avoided.
vi. To minimize the effect of adverse weather, proper precaution should be taken. In hot weather, immediately on completion of concreting, wet cloths must be laid over the wet concrete surface to avoid dehydration. While wind flow velocity is high, similar actions may also be provided. Constant sprinkling of water may also be continued.

5. CONCLUSION

Identification and introduction of “Plastic Shrinkage Cracks” of both 'Shallow depth' as well as of 'Deeper depth' is the prime focus of this paper.

'Plastic Shrinkage Cracks of Shallow Depth' is quite well known to the Engineers. Conventionally this shallow depth cracks are also called 'Surface Crack'. Hence, more stress has been given in this paper on 'Plastic Shrinkage Crack of Deep Depth' and more technical analysis has been placed on this aspect for convenience to the young site Engineers.

The exact introduction of the deep crack is generally not well known to the Engineers. The concept on this issue, as described hereinabove, may be helpful to the site Engineers.

Besides the said identification and introduction of 'Plastic Shrinkage Cracks of Deep Depth', the gist of the paper is highlighted hereunder in respect of cracks as –

- The last (top) layer pour of concrete is very vital to determine depth of the cracks.
- Dehydration of concrete is the basic and prime reason of 'Plastic Shrinkage'.
- Vibration in concrete shall be “Optimum”. The concept of this word “Optimum” is required to be realized by the persons, who run the vibrators at site.
- In designed mix of concrete, fine materials shall not be of less quantity for the purpose of maintaining cohesive force (tensile strength) amongst the ingredients of concrete.

Plastic Shrinkage Cracks of Deep Depth may be detrimental to the structure. In view of the same, concept of this paper may be in proper use by the Engineers.

6. ACKNOWLEDGEMENT

The authors are thankful to Mr. Arindam Nandy, Ex DGM of IRCON International Limited for fruitful discussions on Project specific issues in major Rail Bridge having pile caps of depth 3.5 m.

REFERENCES

1. Raina's Handbook for Concrete Bridges – Volume.1 by Dr. V.K. Raina (page 545 to page 594).
2. Technical paper titled “Plastic Shrinkage and Deep Crack Formation in RCC Structures Owing to Excess Bleeding in Concrete and Remedial Measures Thereof” by Dhrubajyoti Bhattacharya and Amitabha Datta, published by 'The Indian Road Congress' 'INDIAN HIGHWAYS' – Vol. 46 / No. 8 : August 2018.
3. IS 9103-1999 & IS 2386 (Part-3)
4. ASTM: C 232-99
5. Relevant Standard Codes.