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Concrete in Residential Construction

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Concrete in Residential Construction

Summary:

Concrete is widely used in residential construction for footings, walls, and slabs on ground. Some of the problems that occur in residential concrete construction are discussed in the report and suggestions for avoiding these problems are mentioned. This report also provides a summary of requirements needed to achieve high quality concrete in residential construction. Aspects include concrete materials, proportions, mixing, placing, consolidation, finishing, curing and formwork. The important recommendations of codes pertaining to residential concrete construction are restated.

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1. Introduction

Concrete is one of the most widely used construction material in the world. Residential construction represents a major market for concrete in the U.S. The main uses for concrete in residential construction include footings, basement walls, and slabs on ground (floor slabs, driveways, sidewalks, and parking areas), however concrete may also be used above ground for suspended slabs, wall and roof systems. The residential concrete industry is least regulated of all segments of concrete industry. Hence, a need was felt to identify the main problems faced during the construction and highlight the important factors to be considered during construction.

1.1 Objective

The main objective of this report is to provide a summary of factors to be considered to produce quality concrete for residential construction.

1.2 Scope

The problems associated with residential concrete construction are discussed and important code provisions are restated for ready reference.

1.3 Relevant agencies and codes

Information on concrete construction is available from organizations such as the American Concrete Institute (ACI), Portland Cement Association (PCA), and National Ready Mix Concrete Association (NRMCA).

ACI Standard “Residential code requirements for structural concrete and commentary" (ACI 332-10) covers the design and construction of cast-in-place concrete one- and two-family dwellings and multiple single-family dwellings (townhouses). ACI 332-10 contains detailed design and construction provisions for footings, foundation walls and slabs-on-ground. ACI 332-10 also provides a report entitled "Guide to Residential Concrete Construction" (ACI 332.1R). The guide provides practical information about the construction of residential concrete. Requirements for multi-story (high-rise) concrete construction are contained in ACI 318-11. For above-grade concrete construction such as suspended slabs, wall and roof systems, reference should be made to ACI 318.

2. Concrete elements

Typical elements in residential building construction include footings, foundation walls and slabs on ground. Detailed information on design and construction of these types of elements is provided in ACI 332.1R-06.

Footings are provided to distribute loads to the soil and to provide a platform for construction of foundation walls and support posts. In addition to distributing the loads to the soils and minimizing differential settlement that can cause cracking in walls above the footing, the footings can bridge isolated areas of settled soil under the footing. Footings should be placed below the frost line and concrete should not be cast in standing water or mud. During cold weather the soil should be protected from freezing before and after concrete placement. A footing drainage system is usually required to minimize lateral loads on foundation walls.

Formwork for concrete walls is supported on the footings. Forms may be re-usable or stay in place. Reusable forms may be made of wood, aluminum, or a wood-steel combination. Stay in place forms are usually made from polystyrene foam forms connected by plastic ties. Horizontal and vertical reinforcement is usually placed in concrete walls to resist applied loads and control cracking due to shrinkage and temperature effects.

Concrete slabs are used as the floor in basement areas, or as the main floor in buildings without basements in residential construction. Elevated slabs spanning between walls or column supports are sometimes, used particularly in multi-occupancy residential construction with several floors above the ground level (Bondy, 2005). Slabs are also used outdoors for sidewalks, driveways, carports, and parking areas. Slabs on ground can be structural plain concrete without reinforcement although reinforcement is often used to control cracking due to settlement, shrinkage and temperature effects.

3. Problems faced in residential concrete construction

The residential sector is the least regulated of all segments of the concrete industry and this leads to several defects in the construction. According to Nasvik (2003), the problem with residential sector is that the guidelines specified by ACI are rarely read and enforced. The decisions at the construction site are taken by the individual contractors and the requirements of air entrainment, slump, curing water-cement ratio, admixtures, control joints etc are ignored leading to the inferior quality of construction.

Jaffe (1988) describes the issues faced during residential construction. The main problem arises due to slow pour of concrete. The concrete from ready mix trucks may not be used within 90 min and water may be added to prevent loss of slump. The added water may not be mixed sufficiently further deteriorating the quality of concrete. To avoid this situation, forms must be in place with sufficient workers to place the concrete when the ready mix truck arrives.

Problems arise due to rapid drying of the surface. Finishers may rewet and then trowel the surface which weakens it. Such surfaces have poor wear resistance and are prone to scaling. To avoid this, surface should be kept wet by covering it with plastic film or by spraying evaporation retardant. By no means, should added water be forced back in to concrete.

Sometimes, the mindset of contractors is that curing is not required in cold temperature because it harms the concrete surface. During cold weather, curing must be done by taking precautions to avoid freezing.

Joint errors are prevalent in residential concrete. The contractors may provide joints that are too far apart or may not be sufficiently deep. This causes cracking of concrete. Joints should be properly placed with sufficient depth. Joints re-entrant corners should be jointed.

A study was carried out when problems like scaling, cracks, pop-outs, discoloration were noticed in concrete houses after the winter of 2000/2001 in Illinois (IRMCA 2002). A task force was formed and recommendations were given for the use of ready mixed concrete for residential sector. IRMCA (2002) specifies that the residential flatwork is unacceptable when it displays major cracking, major scaling of major spalling for the period of one year. These problems may arise due to either defective material or workmanship or may be both.

IRMCA (2002) defines a major crack as "an uncontrolled crack with a width of 1/8” or more that covers more than 10% of the total length of all the joints and edges of the slab and the total length is no more than 20% of the perimeter length of any one panel". Similarly, major scaling and spalling occurs when it covers more than 15% of the total slab or 20% of any one panel. To maintain the quality, the contractors should warrant the work for a certain period of time against failures due to construction procedures, material and workmanship.

With the advent of modern technology, quality can also be maintained by using precast members such as insulating concrete forms (ICF). Because of its several advantages, ICF is becoming very popular in residential construction. According to Portland Cement Association, about 70% of utilization of ICF is in the single family residential construction with remaining 30% for commercial and multifamily purposes.

4. Troubleshooting

To achieve quality concrete in residential construction, careful planning and attention to detail is required at each step of the process. Typical problems encountered in concrete construction include cracking, scaling, blisters, popouts, dusting and discoloration. Troubleshooting concrete problems should usually be left to an experienced concrete professional, however understanding the causes of these defects can help in planning to avoid them.

Because concrete is relatively weak in tension, some cracking can be expected in most concrete construction. The most common cause of cracking in residential concrete is drying shrinkage and temperature effects. Drying shrinkage is caused by loss of moisture during the hydration process. To minimize cracking potential, concrete should be placed with the lowest possible water content and properly cured. Contraction joints using saw cuts need to be sawn early enough, deep enough and not spaced too far apart. Plastic shrinkage cracks near the surface can occur before finishing due to rapid loss of moisture from the top surface (figure 1). Use of wind breaks, sunshades and other means to prevent rapid drying can minimize plastic shrinkage cracking. Other causes of cracking include soil settlement and structural overloading.

Dusting is the development of a fine powdery material due to a thin layer of weak concrete called laitance at the surface (figure 2). This is often caused by floating bleed water back into the surface. It may also be caused by overly wet mixtures, inadequate curing, and freezing at the surface.

Scaling is caused by the loss of surface mortar surrounding coarse aggregate particles, leaving the coarse aggregate exposed. It is usually caused by water freezing in the concrete and lack of air entrainment to relieve the internal pressure due to freezing (figure 3).

Popouts at the surface are usually caused by internal pressure developing due to expansion of unstable materials or chemical reaction between cement and some types of aggregates (figure 4).

Blisters can appear on the surface during finishing due to bubbles of entrapped air forming under an airtight surface layer (figure 5). This can be prevented by using proper finishing procedures and good quality concrete.

Figure 1. Plastic shrinkage cracking

Figure 2. Dusting

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

Figure 3. Scaling of concrete **Figure 4. Popouts**

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

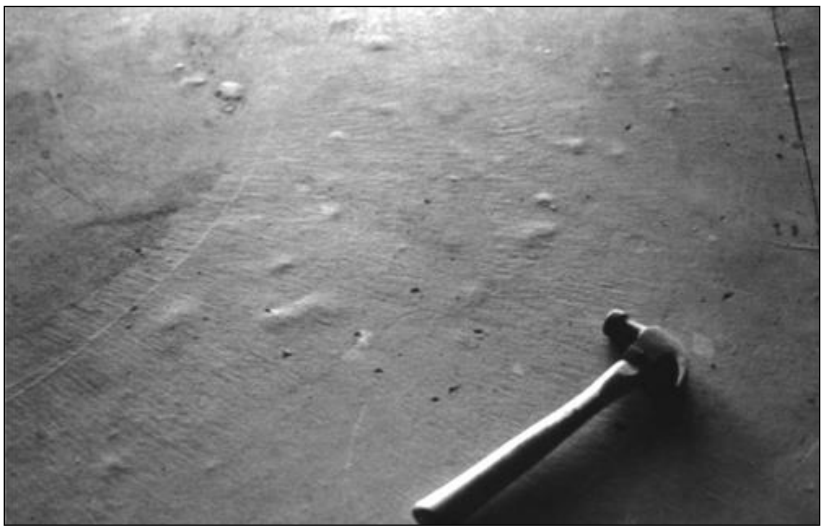

Figure 5. Blisters

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

5. Concrete materials

Concrete consists of cementitious material (Portland cement, fly ash, slag etc), coarse aggregate (gravel), fine aggregate (sand) and water. Admixtures and additives may also be added to produce desired properties. The strength of the mix depends to a large extent on the proportions of these ingredients. Each material in concrete has its own significance and changing proportions alters the properties of concrete significantly. Concrete is usually supplied to the site by a ready mix concrete supplier. Hence, the concrete mix supplier should be consulted prior to altering the proportion of cement, aggregates or water. The information regarding the constituents of concrete is presented in the following paragraphs.

5.1 Aggregates

Aggregates occupy the major portion of concrete by volume and serve as inexpensive filler. Aggregates should be chemically inert so that they do not react with cement or water which might lead to deterioration of concrete. The size, shape, and surface texture of aggregate also affect the quality of concrete. Aggregates should preferably be cubical or rounded. The aggregates size should not be more than one fifth of the narrowest form dimension or one-third of the cross-sectional dimension of a structural member or three quarters of the minimum clear spacing between reinforcing bars. They should be without impurities and well graded.

Aggregates with high absorption should be avoided as they may lead to high shrinkage. Alkali-silica reaction can occur between certain aggregates and portland cement. This can be controlled by keeping concrete as dry as possible or by using blended cements or using fly ash, slag, silica fume materials or certain admixtures.

5.2 Water/Cement ratio

The cementitious pastes consist of cement and water that coats and bonds the aggregates together. This paste also fills the voids between the aggregates. The strength of concrete depends primarily on water cement ratio. If the amount of cement is increased, the strength of the concrete will increase. However, there should be sufficient water present in the mix to hydrate all of the cement. Addition of water more than the specified amount will provide ease of placing the concrete i.e. workability; however, it will decrease the strength of the resulting mix and increase the potential for shrinkage which may further increase development of cracks. Water cement ratio should be preferably less than 0.45. No additional water should be added at the job site to ready mix concrete unless water-cement ratio at the time of batching is lower than the allowable. If the slump is lower than the maximum allowed value, high range water reducing agents may be used. Retarders can be used when the concrete mix truck has to travel a long distance from the concrete plant to the job site so that concrete does not set before it reaches the site. Retarders temporarily stop the action of hydration of cement.

6. Compressive Strength

The compressive strength of concrete used for residential construction should not be lower than 2500 psi. This range is applicable only where the weathering probability is negligible. For construction of driveways, stairs, curbs, slabs which will be exposed to weather, the minimum compressive strength of concrete should not be less than 4500 psi and slump should not be more than 5".

Concrete has a tendency to shrink when it dries. Cracks may develop when shrinkage is restrained. This restraint may result from support conditions, reinforcing steel, connection between different parts of structure etc. Cracks are generated as a result of shrinkage. Since shrinkage is greater at the surface, it generates surface cracks initially. Concrete has low tensile strength. If the tensile stress on a concrete component is greater than the tensile strength, concrete tends to crack. Joints may be provided to control cracking. Concrete may crack randomly in slabs on ground if control joints are not provided to divide the slab into smaller sections. Hence, control joints are created into concrete so that cracking occurs at predetermined locations. These control joints are created by grooving and sawing the concrete surface. Figure 6 shows the creation of control joint in a concrete slab.

Figure 6. Grooving of concrete slab

Source: ACI 332.1R-06 Guide to Residential Concrete Construction

7. Concrete in cold/hot weather

Concrete gets permanently damaged if it is exposed to freezing temperature before reaching a compressive strength of 500 psi. Hence, for cold weather concreting special provisions are needed for maintaining the placement temperature. Insulation products and supplemental heat may be needed to maintain the concrete temperature. Accelerators can be used when casting concrete during cold weather. Accelerators decrease the setting time of concrete to counter the effect of low temperature.

If the ambient temperature is less than 35 °F, concrete temperature should be maintained above 35 °F till the compressive strength reaches 500 psi. Frozen material containing ice should not be used in the mix. Materials coming in contact with concrete like aggregates, reinforcement, form, should be free from frost. ACI 306R provides detailed requirements for cold weather concreting.

Casting concrete in hot weather can also lower the ultimate concrete strength and serviceability of a concrete member. In hot weather, water is evaporated from the mix, slump decreases rapidly and cement sets up rapidly. The water at the surface may dry up quickly and if not cured adequately, it may decrease the ultimate strength. Loss of water may lead to shrinkage and cracking.

Adding more water may compromise the ultimate strength of the mix. Sometimes dry sub grades and formwork can absorb water from the concrete mix aggravating the problem. Thermal differential may set up between two parts of the member which might lead to cracking. Retarders are used in areas where high temperature may decrease the setting time of concrete. ACI 305R should be referred for hot weather concreting.

8. Workability of concrete

The concrete mix should be workable during placement and finishing. Properties like consistency, setting time and bleeding also affect the strength of concrete. Some parameters concerning the casting phase of concrete are discussed below.

8.1 Slump

Consistency of concrete defines the flowability of concrete and it is measured through the slump test. During the slump test, a truncated cone is filled with concrete and the amount by which the concrete subsides is measured once the cone is lifted. If the slump value is high (6"-8"), it means that the concrete is more workable. However, if the water content is more than the designed water content of the mix, it would result in weak concrete. Low slump (1"-3") means concrete is difficult to consolidate and is stiffer. Concrete with low slump is difficult to place and finish. Slump usually varies from 5" - 6". Figure 7 shows the slump test of the concrete mix. The high as well as low slump is depicted in the figures.

Figure 7. Slump test (left: High slump; right: Low slump)

Source: ACI 332.1R-06 Guide to Residential Concrete Construction

The slump value of concrete should not be increased only by adding water as water may make the cement paste thin and reduce the strength of concrete and increase shrinkage. If required, slump can be increased by the use of admixtures.

8.2 Setting time

Setting time is the time concrete takes for initial stiffening once the water has been added to the mix. It can vary from 4 to 8 hrs depending on the mix composition, cement properties, temperature of mix and ambient temperature. The setting time of concrete increases with decrease in temperature.

8.3 Bleeding

After the concrete has been placed, solid material settles down whereas excess water rises to the surface. This phenomenon is known as bleeding. During finishing, this water may get mixed with the surface layer leading to creation of weakened zone and fine cracks, and surface defects such as dusting and scaling. Hence, finishing should not be done while bleed water is present.

8.4 Air entrainment

Air entrainment admixtures help entrain tiny air bubbles in the concrete. This improves the workability of concrete. The amount of water required to achieve a certain consistency also decreases with the use of air entrainment admixtures. As the amount of water decreases in the mix, the strength of concrete increases and the problem of bleed water reduces. The bubbles remain as discrete voids after hardening of concrete. These voids help in releasing the pressure during the freeze-thaw cycle. It is required that concrete subjected to freezing and thawing should have between 5%-8% of entrained air by volume. For regions of minimum weathering probability, there is no minimum air entrainment requirement.

8.5 Placement

The normal discharge time for placement of concrete is 1.5 hours after adding water. This discharge time can be exceeded if the temperature of concrete is in the range of 55 to 100°F and the water amount present in the mixture is not more than the specified mixture proportion.

While placing concrete, care should be taken so that consistency and matrix of the concrete mix is maintained and there is no loss of material. The area should be cleared of debris, ice and excess water before concrete is placed over it. Concrete should be consolidated using vibrators. Extra care should be taken while placing concrete around reinforcement bars, corners of forms and other embedded items so that there is no void around them. Removal of forms should be done in such a way that the surface of concrete is not damaged.

8.6 Concrete cover

Concrete cover for concrete cast against earth should be minimum 3 inches, for concrete exposed to weather or earth, cover should be minimum 1.5 inches and for concrete not exposed to weather and earth, cover should be minimum 0.75 inches.

8.7 Calcium Chloride

Calcium chloride should not exceed 2% by weight of cementitious materials for structural plain concrete in dry areas protected from water. For structural work, plain concrete exposed to atmospheric conditions and reinforced concrete, calcium chloride should not exceed 0.3% by weight of cementitious materials.

9. Curing

The concrete mix loses moisture once it is placed and loss of moisture may lead to improper hydration of cement. Curing is done to maintain adequate moisture and temperature conditions in a freshly placed concrete mix so that hydration of cement takes place and the desired strength of the concrete mix is developed. It has significant impact on strength, permeability, abrasion resistance, and resistance to freezing and thawing of concrete structures. All concrete structures should be cured for the specified period. ACI 308.1-11 contains specifications for curing concrete. ACI 308R-01 provides a report describing current curing techniques and procedures for curing different types of construction.

The curing period is the time period beginning at placing of concrete and extending until the concrete has attained the desired strength. Curing should be started as early as possible when drying conditions exist. For temperatures above 40 °F, curing should be done till the concrete has achieved 70 percent of specified strength. Curing duration should not be less than 7 days for ASTM C150 Type I mix, 10 days for ASTM C150 Type II mix, 14 days for ASTM C150 Type IV & V mix. Curing duration can be decreased if accelerators are used for development of early strength. For temperatures below 40 °F, the concrete must be protected from the effects of cold weather throughout the process of placing, finishing, and curing. During cold weather, heat should be used to maintain the temperature of the concrete, along with proper curing.

The curing procedure can be described in three stages. Initial curing measures such as fogging and use of evaporation reducers are applied between placement and final finishing of concrete. It is done to reduce the loss of moisture from the surface. Intermediate curing is done using spray applied liquid membrane forming curing compounds and is implemented after finishing and before the final set of concrete. Final curing is implemented when the concrete has reached final set. It is implemented through measures such as applying wet coverings or using liquid membrane-forming curing compounds. A complete and continuous water cover should be available over concrete surface for wet water curing. Alternate wetting and drying of concrete surfaces deteriorate its quality. The water should be free from harmful chemicals and impurities. Potable water is acceptable as curing water.

If wet covers are used for curing, they should not be allowed to dry and absorb water from concrete. Curing period should terminate with uniform, slow drying of concrete surface. To achieve this, cover material should be allowed to dry thoroughly before removing it.

10. Consolidation

Consolidation of freshly mixed concrete results in reduction of voids by expelling entrapped air. It leads to a compact mix which has closer arrangement of particles of concrete and has a strong and durable structure. If concrete is not consolidated it may lead to porous, low strength, highly permeable structure. ACI 309R-05 provides information on consolidation mechanism and gives recommendations on available consolidation procedures.

The consolidation requirements are determined by the workability of the mix. While determining the workability, reduction due to loss in slump because of high temperature, premature hardening, etc should be considered. Workability determines the ease with which concrete can be mixed, placed, consolidated and finished. Workability is primarily controlled by water-cement ratio of the mix. When the mix has high ability to flow (contains more water), the mix may segregate during consolidation. Concrete mix with low water-cement ratio requires more effort to achieve proper consolidation. In such cases, admixtures can be added to achieve desired consistence and workability. If stiffer mixes are not consolidated properly, they will contain entrapped air and will be porous resulting in decrease in strength.

Manual and mechanical methods are available for consolidation. Consolidation is usually done by vibration, centrifugation (spinning), spading and tamping. The consolidation method depends on the concrete mix, placing conditions and amount of reinforcement. If the mix has flowing consistency, rodding may to done to consolidate it. Spading is done in the formed concrete surface. If the mix is stiff, hand tamping may be done to consolidate the mix. While applying these methods, a thin layer of concrete is laid and rammed. Consolidation obtained through manual methods is effective but is time and labor intensive.

Mechanical methods consist of the use of equipment that applies static pressure, power tampers, centrifugation, shock tables, and vibrators. Two or more methods can be used together. Vibrators are predominantly used for consolidating concrete (figure 8). Vibratory impulses induced by vibrators, liquefies the mortar and internal friction between particles results. When internal friction decreases, concrete is not able to support its honeycomb structure and becomes unstable. While in this condition concrete becomes denser eliminating the honeycombs (figure 9). Once the vibrations are stopped, internal friction is again established. Agitating the mix further forces the entrapped air to rise to the surface. The vibration should be terminated when entrapped air is reduced sufficiently.

Figure 8. Vibration of concrete

Source: ACI 303R-12 Guide to Cast-in-place Architectural Concrete Practice

Figure 9. Honey Combing

Source: ACI 201.1R-08 Guide for conducting a visual inspection of concrete

11. Concrete formwork

11.1 Design

Formwork should be able to support all vertical and lateral loads applied to the structure. Formwork should be constructed to provide the correct dimension, elevations, position, shape and alignment to the structure. Formwork should not be supported on frozen ground. ACI 347-04 provides guidelines regarding design, construction and material of formwork.

11.2 Construction

Formwork can fail due to use of substandard materials & equipment, inadequate design and human error. It is important to supervise and inspect formwork throughout its erection till its removal. Safety measures should be followed for safe installation. The details of scaffold, working platforms and guard rails should also be included in the design and drawings.

Construction deficiencies may lead to failure of formwork. Hence, formwork should be continuously inspected for abnormal deflections or behavior. Installation should be done as per the drawing. Sufficient number of nails, bolts welds should be provided. It should be properly braced. Rate of placing concrete should be maintained as per the design documents.

Studs or shores should be properly spliced. Joints and splices should be staggered. The fasteners should be properly tightened. There should be no gap in the form from which loss of mortar may occur. The joints should be provided as per the contract document. For construction of sloping surface with slope more than 1.5 horizontal to 1 vertical, a top form should be provided. Concrete should not be placed on formwork containing dirt, mortar, or any foreign material. Any extraneous material should be cleaned from the surface and a release agent should be applied before using the formwork.

Several practices should be followed before concreting. Formwork should be properly anchored to prevent its movement. Provisions for realignment and readjustment of shores in the case of settlements should be provided. Additional elevation of formwork should be provided to allow for certain irregularities. The elevation, camber and alignment of formwork should be continuously checked during and after concreting. Any corrective measures, if required, should be quickly take to prevent further damage.

11.3 Removal of formwork

The formwork should only be removed when the concrete has attained its minimum strength. The strength can be determined by testing job cured specimens or in place concrete or using procedures like maturity method, penetration resistance, pullout tests etc as specified by ACI 228.1R. The concrete should not have excessive deflection or damage due to removal of formwork. If the forms are removed before the curing requirements are complete, curing should be done as per ACI 308R-01. Proper measures should be taken to protect concrete from the cold weather. The supporting forms for structural members should not be removed till the time they are able to carry their own load and superimposed load. In some cases permanent forms can be used which do not require removal and become a permanent feature of the structure. Permanent forms can be rigid or flexible. Rigid forms consists of wood, plastic, metal deck, fiberboard, precast concrete (figures 10 and 11). The flexible form consists of reinforced, water-repellent, corrugated paper, or wire mesh with waterproof paper backing.

Figure 10. Metal framework with plywood sheathing faces

Figure 11. Aluminum forms

Source: ACI 332.1R-06 Guide to Residential Concrete Construction

11.4 Economy

In the United States the cost of formwork can be as high as 60% of the total cost of the completed concrete structure. The cost of formwork can be reduced by proper planning and design of structure. When the dimensions of footings, columns, and beams are in standard multiples, formwork can be reused, increasing economy. The number of sizes in a structure should therefore be minimized. If the design of the structure is based on one standard depth, the cost of formwork will be reduced. Using readymade formwork and keeping sizes of joist constant will lead to speedy construction and thus reducing labor cost.

12. Conclusion

Concrete construction has been and will continue to play a major role in residential construction. High quality concrete construction requires careful planning and attention to detail at phases of the process. This report provides an overview of aspects that need to be considered to ensure a high quality product. An effort is made to identify the common problems encountered during the residential concrete construction and suggest solution to avoid these problems. Efforts should be made to make available to the housing industry, training programs to ensure that recent advances in concrete technology can be implemented in the construction of housing.

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