Introduction

Portland cement based concrete is today the most widely used material of construction.

Concrete has attained this pre-eminent position because of many useful properties it is endowed with. Among these properties are the relative ease of formability, rigidity on setting and curing, and the great ability to resist compressive forces (generally in the range of 20-80 MPa and in special cases up to 280 MPa).

Concrete is, however, weak in its resistance to tensile forces, flexural tension, shear and torque. It tends to be brittle in nature.

These weaknesses are overcome with the addition of reinforcing bars (rebars) of steel in the case of reinforced concrete and high strength steel wires or cables in the case of prestressed concrete.

With its weaknesses overcome and its positive properties retained, beautiful concrete structures have given expression to man's imagination and sense of elegance.

The utility and elegance as well as the durability of concrete structures, built during the first half of the last century with ordinary portland cement (OPC) and plain round bars of mild steel, the easy availability of the constituent materials (whatever may be their qualities) of concrete and the knowledge that virtually any combination of the constituents leads to a mass of concrete have bred contempt. The same thing happened in the case of rebars as bars of higher and higher strength of a radically different type were introduced. Strength was emphasized without a thought on the durability of structures.

As a consequence of the liberties taken, the durability of concrete and concrete structures is on a southward journey; a journey that seems to have gained momentum on its path to self-destruction (Figures 1–7). This is particularly true of concrete structures which were constructed since 1970 or thereabout by which time (a) the use of high strength rebars with surface deformations (HSD) (Figure 8) started becoming common, (b) significant changes in the constituents and properties of cement were initiated, and (c) engineers started using supplementary cementitious materials and admixtures in concrete, often without adequate consideration.
Common features among the examples in Figures 1-7 are: (a) all the concrete structures, whether roofs or not, are exposed to the atmosphere, and (b) all the structures contain reinforcing bars (rebars). These bars are in the form of high strength bars with surface deformations (Figure 8).

Today, it is not uncommon to find instances of distressed concrete elements inside rooms, tunnels, etc., away from any known sources of water, other than atmospheric air, suffering early distress due to corrosion in rebars.

Figure 9. Self-destruction of concrete through volume expansion due to swelling of gel which is formed on the surface of aggregates (containing reactive silica or silicate) by reaction of reactive silica or silicate with alkali in cement in a process known as alkali-silica reaction.

Figure 9 shows another form of distress in concrete that can occur more often in constructions with modern cement.

The setback in the health of newly constructed concrete structures prompted Swamy\(^1\), to write: “The most direct and unquestionable evidence of the last two/three decades on the service life performance of our constructions and the resulting challenge that confronts us is the alarming and unacceptable rate at which our infrastructure systems all over the world are suffering from deterioration when exposed to real environments.”

The observation of Swamy\(^1\) is an echo of the observation which was made in a 1999 document of Central Public Works Department, Government of India\(^2\) when CPWD reported in its Technical Circular 1/99 that while work as old as 50 years provided adequate service, the recent
constructions in concrete were showing signs of distress within a couple of years of their completion.

The plight of reinforced concrete structures of recent vintage has made such structures yearn for the healthy life of the past when concrete structures could expect to have long life spans.

Though it is an international phenomenon, the problem of early distress in concrete structures is most acute in India, where cold twisted deformed (CTD) rebars were most extensively used during the last three decades of the last century.

Being widespread and universal, the tailspin in the life span or durability of concrete structures, constructed in recent decades, came as a surprise to many, specially when concrete was going through the stages of gaining in compressive strength from 10-30 MPa of earlier periods to a more common 20-80 MPa of these days and in special cases up to 280 MPa, with a newly found label of high performance concrete. This surprise finds expression in the words of Swamy\(^1\) who, being surprised at the alarming and unacceptable rate of deterioration in the condition of infrastructure systems, writes: “What is most surprising is that this massive and horrendous infrastructure crisis has occurred in spite of the tremendous advances that have been made in our understanding of the science engineering and mechanics of materials and structures.”

The surprises and disappointment emanate from a failure to recognize or admit the real causes of the problem. It is pertinent to note that the unhappiness with the performance of concrete structures followed many thoughtless changes in rebar, cement and construction practices.

In all these changes, the emphasis in the case of rebars was on higher strength. In the case of cement, the emphasis was on higher strength, high early strength and greater profit margin, whereas in the case of construction practices, the emphasis has been on doing away with or shortening the period of moist curing.

The changes in the principal materials of concrete construction are perpetuated through various provisions in the basic Indian Standard for the design and construction of concrete structures, IS:456-2000\(^3\), when the standard or code makes no distinction among reinforcing elements of steel of different categories and grades, of shapes as different as plain bars and bars with surface deformations, as disparate as round bars and structural shapes, or among OPC, Portland slag cement (PSC), Portland pozzolana cement (PPC) and seven other types of cement, except may be in the required duration of wet curing of concrete, made with different types of cement.

It will be shown later that, as in the case of reinforcing elements, the Indian codes also provide too much leeway in the requirements for individual types of cement.

In addition, what could be most disturbing is a general lack of discipline in India in the matter of adherence to the codal provisions on the properties of the manufactured materials. A few examples, related to the construction of a single family dwelling in Kolkata in the year 1993, will illustrate the point. It will make one recognize the sufferings and anguish of a reinforced concrete structure and its yearnings for rebars with an unblemished character and cements with an unquestionable performance.

Case 1: CTD rebars of all sizes from 8 mm to 32 mm dia were purchased from the largest steel maker in the private sector in the country. Bars of all sizes were found...
to lack utterly in ductility. All bend tests led to brittle failure. The selling company initially claimed to have the requisite test certificates. A site visit by their representatives was convincing enough for them to recognize and admit the hollowness of their earlier claim of conformance of their product with the provisions in BIS standards. All bars, except the 32 mm dia bars, were replaced over a period of about two months. So difficult it was for the largest manufacturer of steel products to find rebars conforming to the standards that money was refunded for their failure to locate and supply 32 mm dia bars which would meet the requirements of BIS standards. It will be seen later in this paper that compliance with the requirements of the relevant standards of BIS would not necessarily make the CTD bars suitable for the construction of durable concrete structures.

Case 2: For the construction of the same building, for which rebars were procured in Case 1, PSC was procured from a leading manufacturer of cements. The cement was procured fresh from the rail wagons. The cement was used in construction on the following day. A day later, as one approached the site, streaks of slurry, which had escaped through the joints of formwork the day before, were found to glisten like fresh snow in sunlight. Obviously, something was wrong and yet the manufacturer, as in the case of the CTD bars, would routinely issue a test certificate claiming conformance with the relevant code of the BIS.

Case 3: though not cement or rebar, machine made modular bricks of burnt clay, considered to be the best in Kolkata, were procured from the Brick Directorate of the Government of West Bengal for the construction of the building in Cases 1 and 2. The bricks, in place, showed serious signs of distress as well as efflorescence due to high contents of aluminium sulphate. The Director of the government organisation would not initially believe it to be possible. He visited the site, saw distressed bricks in place and conducted some tests on unused bricks whereupon he had no hesitation in exclaiming that the bricks were not suitable for building construction. Bricks, which were yet to be used in construction, were withdrawn and money was refunded. Obviously, the best bricks in town would not satisfy the requirements of the BIS standards.

Such manufactured materials would not make durable structures, and yet such can be the quality of manufactured construction materials in India. The problem is magnified when, as it will be shown later in this paper, the code in Ref. 3 and similar codes in India and abroad recommend for use materials which are incapable of giving durable concrete structures.

Though it can be easily recognized that the satisfactory performance of concrete structures, built with plain round bars of mild steel and OPC in the past, played the key role in making concrete structures durable and popular, it cannot be overlooked in this context that relatively new concrete structures, with signs of distress, started becoming a common sight, only after the start of the use of rebars and cement of modern era, which are distinctly different from similar materials of the past.

Principal Causes of Early Distress

The decay and distress in concrete structures have in most cases been in the form of corrosion in reinforcing bars and consequent cracking and spalling of surrounding concrete.

There must be reasons for the early corrosion in rebars.

A change in the environment over the last four decades cannot be that reason, as co-existing concrete structures of different periods show remarkably different performances; older structures, constructed about forty years ago or earlier, performing better than structures which were constructed during the last thirty years or so.

As the differences in internal forces at service load conditions, as would be determined by different methods of design, are not very significant, the switch-over from the working stress method of design of earlier periods to the ultimate strength or limit state method of design is not one of the prime reasons for the very significant downfall in the durability of concrete structures of recent decades.

That brings into focus the use of inappropriate materials and poor workmanship as likely causes of early distress in concrete structures of recent decades. Poor workmanship was there earlier too as it is today. But the all-pervading nature of concrete structures of recent era reaching states of distress at an early age cannot be explained by poor workmanship alone.

From the three case histories in the preceding section, specially when the eminent positions of the manufacturing firms and their reputation are taken into account, it can be easily visualized that substandard materials are very extensively used in construction in India, and the use of manufactured materials of substandard qualities can have a significant role in the early decay and distress in concrete structures in India. But this cannot still explain the all-encompassing nature of concrete structures of recent vintage, whether in India or abroad, reaching states of distress early.

It is explained in the following that there are certain inherent features in today’s rebars and cement, which contribute to the shortening of the life span of concrete structures in India and abroad.
A survey\cite{5,6} of several randomly selected buildings and bridges in the public domain in Kolkata revealed that structures with CTD rebars (a special form of high strength deformed or HSD rebars) would become distressed early, no matter what the type of cement was. Also, since corrosion in rebars must have something to do with the properties and characteristics of rebars and since such corrosion does lead to distress in concrete structures this should confirm that the principal cause of early corrosion in rebars, and therewith the principal cause of early distress in today's concrete structures, must lie with the rebars.

Besides the time dependent distress in concrete structures, initiated by corrosion in rebars, there are many instances of concrete elements (both reinforced and prestressed) with almost instant signs of concern, like cracks in new concrete structures. As the orientation and almost instant occurrence of the cracks cannot be related to corrosion in rebars and as time dependent damages, of the type depicted in Figure. 9, cannot be related to corrosion in rebars and in prestressing elements, such distresses should be identifiable with shortcomings in cement or concrete. It will be seen later that many of these distresses can indeed be related to the significant changes which were brought upon in the physical properties and chemical compositions of cement of modern era.

The roles of rebars and cement in causing early decay and distress in concrete structures of recent periods thus form the focus of study in this paper.

**Surface Deformations in Rebars Largely to Blame**

Since it was observed in a survey\cite{5,6} that concrete structures with CTD bars performed less satisfactorily than concrete structures with plain round bars of mild steel and since it was also observed that early signs of distress in concrete structures in different countries started showing up with the use of rebars with surface deformations (whether CTD or other HSD bars), it should be obvious that this early decay and distress has much, if not all, to do with HSD rebars.

In the matter of corrosion of steel, engineers tend to think of the possible susceptibility of steel only in terms of its metallurgy. It is generally overlooked that the contour or surface characteristics too can have a significant influence on the corrosion of a piece of steel.

Kar\cite{4-7,9-12} had explained how the presence of surface deformations made HSD rebars inherently prone to early corrosion. It was also explained as to why CTD bars (as in Torsteel, TISCO, etc.), with built-in (manufacturing stage) stresses beyond yield, were the worst of all HSD rebars in the context of early corrosion.

For an understanding of the basic causes of early distress in HSD, HYSD or CTD rebars, it will help to recall the phenomena of stress concentration and stress corrosion. According to the phenomenon of stress concentration, unless there will be an yield, the stress at a discontinuity or deformity can be significantly (even several times) higher than the average or nominal stress across the section. Thus, unlike in the case of a round bar with plain surfaces, the stresses in the surface region of a CTD or HYSD or HSD rebar can be much higher than the average or nominal stress across the section. The stresses in HSD bars may reach yield or higher levels under service load conditions or even before use in construction. The phenomenon of stress corrosion, in the context of the nature of the problem under consideration, implies that metals corrode faster with an increase in the stress level, particularly if stresses will reach yield levels or higher. Initially described in Ref. 5, this phenomenon of stress corrosion is further explained here.

The worst performance in the case of concrete structures with CTD reinforcing bars has its source largely in the manufacturing process of CTD bars. The cold twisting beyond yield, as a part of making CTD bars, causes permanent slippages at the interfaces of metallic grains of steel. High stresses at or above yield stress levels are permanently locked in the bars.

The permanent slippages at the interface of metallic grains, caused during the cold twisting of CTD bars, and the higher strain, under greater stresses from the imposed loads lead to a break down of the protective oxide film on the surfaces of rebars, thereby exposing the intergrain faces of CTD bars to corrosive elements, (e.g., moisture and oxygen) and leading to the formation of electro-galvanic micro cells and generation of damaging electrical currents thereby making the CTD reinforcing bars much more vulnerable to corrosion than would have been the case with plain round bars of mild steel or even with conventional HYSD bars. This can be seen in a comparison of the conditions of rebars in Figures. 10-13.

The top four bars in Figure. 10 with corrosion on entire surfaces show the effect of cold twisting beyond yield as a part of the process of making CTD bars. In Figure. 10, the four untwisted bars at the bottom, which are from the same rod as the top four bars are, show isolated signs of corrosion at the bases of protrusions due to the magnification (effects of stress concentration) of manufacturing stresses even without cold twisting.

It should be evident that CTD bars are a deterrent to the
The recognition of unsuitability for use, though not of the basic reasons for this unsuitability in the case of CTD bars, led to the stoppage of use of such bars fairly early in most countries and a belated introduction of thermomechanically treated (TMT) bars in India.

In the absence of the cold twisting, i.e., in the absence of yield (or higher) stress all over the surface, these TMT and other HSD rebars may not be as bad as CTD bars (Figures 10 and 11) are, but these bars too can be highly susceptible to early corrosion (Figures 12 and 13), as HYS or other HSD rebars suffer from the effects of stress concentration due to the presence of surface deformations and the consequent effects of stress corrosion and other factors.

Figure 13 depicts HYS rebars of good quality at a construction site in the USA. Stress related corrosion can be seen at bends and at cut ends of rebars.

At bends, stresses in plain round bars of mild steel too reach yield. However, in the absence of adequate ductility, the adverse effects of stresses beyond yield are more pronounced in the case of HSD rebars than in the case of plain round bars of mild steel. Also, unlike in the case of HSD rebars in concrete with blended cements, the localized corrosion at bends of plain round bars of mild steel inside OPC concrete is not transmitted.

A unique feature of HSD bars, inclusive of HYS and CTD bars, is that the thin edges of the lugs, which have no specific design requirements in India, are often damaged during the making, transportation and handling. The profusion of nicks in the lugs, arising from manufacturing defects and handling operations, can be easily seen on most products of CTD or other HSD bars. The damaged regions lead to the creation of sites with potential differences. Gradually the whole lengths of bars are covered with rust.

As explained in the preceding, topping the list of factors, which make reinforced concrete structures with HSD rebars so strongly predisposed to early decay and distress, are the phenomena of stress concentration and stress corrosion. Extensive tests and observations in Russia have revealed that, compared to the durability of plain round rebars, the durability of rebars with surface deformations is one order of magnitude less.

Tests in Russia further revealed that, as the state of stresses at the level of yield limit and beyond was associated with considerable impairment of the steel surface and a breakdown of the natural protective oxide film of Fe$_3$O$_4$ or FeO, the HSD rebar, stressed at yield or beyond, became electrochemically more active than an unstressed reinforcing bar and the passivation of such a highly stressed rebar became very difficult even in a saturated solution of Ca(OH)$_2$.

In other words, it becomes well nigh impossible to mask the electro-potential of a rebar inside concrete if surface stresses in the...
steel elements would cross the yield level. Deformed rebars are beyond redemption.

Furthermore, inside concrete structures, the process of rebar corrosion in HSD rebars is at a very active state, as besides heightened stresses in keeping with the phenomenon of stress concentration and stress corrosion, particularly under post yield states, the presence of surface deformations on rebars of recent eras leads to gaps between rebars and concrete\textsuperscript{7,14} and greater microcell and macrocell formations\textsuperscript{15} than in the case of plain round bars in concrete.

Confirmation of the poor performance of HYSD and other rebars with surface deformations is also recorded in the findings of Mohammed, et al\textsuperscript{15}, who concluded on the basis of tests for specific performance that “Due to the formation of gaps, the bottom part of horizontal steels shows significant macrocell and microcell corrosion …………..Deformed bars corroded more than plain bars.”

In the context of durability of concrete structures, it is evident from the preceding that it was most inappropriate when plain round bars of ductile mild steel were discarded in favour of CTD or other forms of HSD bars with limited ductility which are highly prone to early corrosion.

Since rebar corrosion is in many cases at the root of early decay and distress in reinforced concrete structures and since physical characteristics of rebars of recent periods are largely to blame for this poor performance, concrete structures yearm for a switch back to the use of plain round bars of mild steel as rebars which will have high ductility and where stresses at service load conditions will not cross or reach the yield.

Rebars with Surface Deformations Are beyond Redemption

The vulnerability of HSD rebars cannot be camouflaged. Rust shows through epoxy coating in the advertised sample in Figure. 14.

Kar\textsuperscript{16} explained that at added cost, fusion bonded epoxy coating did not provide any assurance of added life span. In addition, the coating prevented any intimate bond between rebars and concrete as a result of which there could be disastrous consequences under vibratory loads.

Figure 15, which is from another advertisement on pretreated HSD rebars, is an admission (by suppliers of galvanized and epoxy coated rebars) of the fact that on its own neither galvanizing nor FBEC can really mitigate the problem of early corrosion in HSD bars. The advertised HSD rebar in Figure. 15 has both galvanizing and FBEC treatment. At much added cost, the twin protection (Figure. 15) will still make the structure vulnerable due to the loss of an intimate bond between the rebar and its surrounding concrete.

Cement

With the use of high strength rebars with surface deformations, the situation is bad in the realm of today’s concrete structures. It has the potential of going from bad to worse with

a) the use of cement which is sold before tests are completed whereas subsequent tests at independent laboratories occasionally show the failure of the cement to meet the requirements set in codes
b) the use of OPC with high C\textsubscript{3}S/C\textsubscript{2}S ratios
c) the use of cement with excessive contents of water soluble alkalis
d) the use of cement with high contents of gypsum
e) the use of PPC with the addition of fly ash without any verification (in India) of its properties for its suitability for use in cement
f) the use of PSC that may be made with ground granulated blast furnace slag of unverified qualities
g) the use of PPC and PSC which will be made with OPC clinker of the type described in (b)–(d)
h) inadequate curing of concrete with the availability of OPC, PSC and PPC for general purpose use in India, cement is very often used on consideration of cost and brand name, rather than suitability for specific purpose.

Cement and Impediments to Durability

In the light of (a) past experience of good performance of concrete structures built with OPC, (b) the non-availability of OPC in many
parts of India, and (c) aggressive marketing by manufacturers of blended cements in favour of blended cements, the debate goes on as to whether OPC or blended cement should be preferred for the construction of reinforced concrete structures. It has, however, been suggested in the preceding that properties of modern cement may have a role in the early distress in concrete structures of recent periods. Thus, before a judicious consideration can be given to this issue of superiority of OPC or blended cement, it will help to know more about the changes which have taken place in the case of OPC over the years and the likely consequences of such changes in the context of durability of concrete construction.

The significant changes, which have been brought upon OPC over the years, are:

a) higher specific surface of cement that gives higher strength of concrete as well as higher heat of hydration; with specific surface which today varies between 300-450 sqm/kg, as compared to 150-200 sqm/kg of earlier periods; today's OPC can truly be termed as high early strength cement.
b) large C\textsubscript{3}S/C\textsubscript{2}S ratios in OPC that gives high early strength with little reserve for any gain in strength at later ages; these days C\textsubscript{3}S/C\textsubscript{2}S ratios in the case of OPC is in the range of 3.0 to 5.0; in comparison, the C\textsubscript{3}S/C\textsubscript{2}S ratio was about 0.21 in 1920; about 0.47 in 1970; 0.54 in the late 60's and about 0.56 in 1990 in the USA; besides the lack of any gain in strength with time beyond the initial few days, high C\textsubscript{3}S/C\textsubscript{2}S ratios give high heat of hydration; porosity of concrete is higher and concrete lacks durability as it is deprived of autogenous healing that helps to seal cracks and pores under moist or humid conditions.
c) high contents of water soluble alkalis in cement, is shown in Table 1; high alkali contents can lead to destructive alkali-silica reaction if the %Na\textsubscript{2}O\textsubscript{effective}, i.e., % Na\textsubscript{2}O + 0.658(%K\textsubscript{2}O) will be greater than about 0.6; aggregates with reactive silica or silicates, which react with high alkali (pH > 13.5), are widespread in India and OPC or even blended cement in India today have high alkali contents (Table 1).

The data on contents of water soluble alkalis, as shown in Table 1, are for some cements of well known brands, which were available in Kolkata in the year 2006. Compared to the safe limit of about 0.60, the % Na\textsubscript{2}O\textsubscript{effective} for OPC, PSC and PPC in Table 1 are respectively 2.37, 1.76 and 1.64 which are way too high, compared to the safe limit of about 0.60%.

The consequences of high specific surface, large C\textsubscript{3}S/C\textsubscript{2}S ratios and high contents of water soluble alkalis can be seen in Figure 18 where, unlike the familiar rising curve, there is no gain in the compressive strength of concrete with continued curing beyond 14 days.

Figures 18-22 show the behavior of some cements (of well known brands) which were available in Kolkata in the year 2008.

Greater details on hitherto unknown short term performance of some of today's cement can be found in Ref. 19.

Table 2 shows that today's codes on cement, as in the case of reinforcing elements, may be too permissive to accommodate all that is manufactured.

The high value of the initial setting time, the low figure for the final setting time and the closeness of the initial and final setting times of the cement in Table 2 are indicative of the fact that today's cement may be significantly different from cement of earlier decades. There are no records of durable concrete structures built with cement of the present period.

It will help to recognize in this context that small scale short term tests on laboratory models do not adequately represent the real structures out in the open environment, which are not built with any special attention given to conducting tests.

The significant delay in the initial setting time is due to high contents of gypsum. The effects of such high contents of gypsum on the durability of concrete is yet to be studied.

The above explains why the durability of concrete structures of recent vintage has many impediments.

**Yearnings of today's Concrete Structures**

In the light of the pitiable performance in terms of durability,
today’s concrete structures yearn that serious thinking, divorced from manufacturers’ commercial interests, be given to rebars and cement if the objective will be the construction of durable concrete structures.

Concrete structures yearn that, instead of the hollow promises of the past four decades, they be given back their normal life of the past where rebars and cement/concrete of unquestionable integrity were compatible and complemented each other, thereby leading to a long life.

**Concluding Remarks**

Compared to durable concrete structures of the past, concrete structures, built during recent decades, have been characterized by early decay and distress. Many people have expressed their concern at the unacceptable and alarming rate of decay.

The paper identifies the use of high strength rebars with surface deformations, in lieu of plain round bars of mild steel, as a key factor contributing to the early decay and distress in the case of reinforced concrete structures.

The paper has further identified large specific surface of cement particles, large C / C ratios for compounds in OPC and excessive contents of water soluble alkalis Na₂O and K₂O in cement rendering modern cement unsuitable for the construction of durable concrete.
Structures. The paper has also cautioned against the use of fly ash and granulated blast furnace slag in the making of blended cements without verification of the properties of such materials. Questions have been raised also on high gypsum contents in cement.

As it is generally desired or required that concrete structures be durable, the above factors, which have robbed concrete structures of their durability in recent decades, require re-consideration and improvement.

It will be equally important that codes recommend materials which will give durable concrete structures and not what manufacturers make. It should be ensured simultaneously that manufacturers make rebars and cement to more exacting standards of the relevant codes.

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