IN TRIBUTE TO RASHEEDUZZAFAR

R. N. Swamy*

Centre for Cement and Concrete
Structural Integrity Research Institute
University of Sheffield

When I was invited to prepare a paper in tribute to Prof. Rasheeduzzafar for inclusion in the theme issue of the Arabian Journal of Science and Engineering devoted to Corrosion, I had not fully realized the mammoth task to which I had committed myself. I had met Rasheeduzzafar many times and was exposed also to his many kindnesses and bounteous hospitality. With the clear memory of a gentle giant of a man of supreme technical excellence, his cruel and unexpected removal by the hand of fate from the mainstream of life when he was just beginning to give shape to the dream of his life in the form of his newly-appointed Vice-Chancellorship of Hamdard University in India appeared to be so futile and inexplicable, that I readily accepted the opportunity to bring to life some of the greatness that characterized him throughout his life.

It was through published research that I first came to know of Rasheeduzzafar. It soon became clear that his name and research work were fast becoming synonymous with concrete technology and design, and more importantly, with the corrosion problems in the Arabian Gulf area. His was a determined attempt to fathom, unravel, and diagnose the scientific basis for this unacceptable form of material and structural degradation, and develop an engineering solution to eradicate the disease once and for all. It is in this respect that his research work will live and be remembered for many years to come. I envy all those young scientists and engineers who had the opportunity to study and work with him — little would they have gleaned, at the initial stages at any rate, of the inner man, who constantly battled with ideas and concepts in an effort to extricate the science of concrete and steel corrosion from the real but unpredictable effects of the climatic conditions and environment in which structures breathe and live.

It is to this total commitment — a dedicated, surgical approach to assess, evaluate and evolve a rational and lasting antibiotic — to the problems of the construction industry that a major part of his engineering life was devoted. King Fahd University of Petroleum and Minerals in Dhahran, where he worked, soon realized and recognized this and awarded him twice, first in 1988 and then again in 1992, the Distinguished Researcher Award. A member of the ACI Committee 201 on Durability of Concrete and the RILEM Technical Committee 94–CHC – Concrete in Hot Climates, he was a much sought after chairperson at national and international conferences. He

*Address for correspondence:
Director of Research
Dept. of Mechanical and Process Engineering, The University of Sheffield
P.O. Box 600, Mappin Street, Sheffield S1 4DU
United Kingdom

was a distinguished keynote speaker and uplifted many an academic and engineering gathering with his clear and thorough exposition of the underlying complexities and factors contributing to the deterioration of concrete and steel exposed to real environments. Those who participated in the International Conference on Corrosion and Corrosion Protection of Steel in Concrete held at the University of Sheffield in July 1994, will remember his masterly presentation, as well as his deep grasp and comprehension of the subject matter that has intrigued and fooled many researchers over a long period of time. It is this unique ability to understand the interactive and interdependent parameters of the deterioration process of concrete and combine them into a coherent, meaningful whole that has distinguished the scientific career of Rasheeduzzafar from that of the rest of us.

What is perhaps unique, but not surprising in a personality such as that of Rasheeduzzafar, is the combination of his role as a teacher along with that of a researcher. He was nominated four times for the Best Teacher Award — in 1988, 1989, 1991, and 1992 — by the Civil Engineering Department of King Fahd University. These are achievements unparalleled in academic life, to be so appreciated by the younger generation, and are attained by few academics who are often classed as either excellent teachers or outstanding researchers, but not credited with excellence in both.

The greatest achievements of Rasheeduzzafar, as an academic and scientist, were in the field of research. His contributions to published work span a period of three decades. Of these the last twenty or so years were almost totally devoted to the study of corrosion of steel and deterioration of concrete in the Gulf environment. The nature of the problem he tackled is probably one of the most complex encountered within the construction industry. To understand the problem, let alone solve it, requires a life time of systematic, planned research, an understanding of mathematics, physics, and chemistry, a combination of testing and analysis, and the ability to think through a series of interactive phenomena. That Rasheeduzzafar was able to achieve this to a great extent, before he was cruelly snatched away from life, is a standing monument to the quality of a penetrating and discerning mind. It is impossible to do justice to this unusual and remarkable quality of an engineer and scientist in a short paper such as this. What follows is a simple, and most likely, feeble attempt to put into perspective the results of a life-time of study and research into a perplexing phenomenon which in real life has no easy or single solution. However, in highlighting some of the issues that Rasheeduzzafar so ably and consistently pursued, it is hoped that something of his greatness will shine through.

One of the first tasks, and a major element at that, of Prof. Rasheeduzzafar's work was his recognition of the seriousness and importance of the interaction of concrete with the environment, beyond the generally accepted and traditional role of a concrete to carry external loads [1, 2]. In the aggressive service environment of the seaboard of the Arabian Gulf where most of Rasheeduzzafar's work was carried out, the construction industry had to respond to unprecedented demands in the context of inadequate infrastructure, lack of suitable materials, equipment, and skilled manpower, together with inadequate specifications and construction practices. Environmental factors such as high temperature–humidity regimes and salinity in the ground and ambient air conditions are the greatest enemies of concrete, even when the material and construction techniques are of the highest quality: in the Gulf context, the unique combination of the inadequacies of the industry and the severity of the geomorphic and climatic environmental conditions accentuated an alarming degree of deterioration within a short span of 10–15 years. To Rasheeduzzafar goes much of the credit in establishing this close and complex interaction between concrete as a material, and construction practices, and the environment which they have to serve. He identified the major causes of deterioration and prescribed the solutions to obtain improved durability of new concrete construction.

Rasheeduzzafar immediately recognized the major difficulties associated with corrosion studies facing researchers in this part of the world, namely, how to establish a meaningful and rational interrelationship between laboratory studies and field performance of concrete as a material and concrete structures. Laboratory tests are often carried out to simulate causal factors such as sulfate attack or chloride penetration, but the results have often proved difficult to interpret in terms of field performance. Experience has shown that they often fail to provide a reliable estimate of concrete deterioration under actual interactive factors. Field studies, on the other hand, are much more difficult to carry out and pose a large number of headaches in their planning, execution, and analysis of data. Sampling, for example, to evaluate the in-situ deterioration of concrete is bound to be significantly different from that one could use for quality control and acceptance tests at the production and placing stages of concrete.

Rasheeduzzafar recognized these difficulties in field studies and appreciated that the inherent variability of concrete, even when manufactured under the best of quality controlled conditions, will be compounded by subsequent variables in placement, consolidation, curing, and actual exposure conditions. On top of all this are the regional characteristics such as variable and poor workmanship, lack of a trained workforce, adequate supervision and quality control. To separate these influences in a rational manner, and yet get to the bottom of the problem, is a gigantic process that calls for perspicacity, firmness of purpose, and resoluteness.

In spite of these limitations and challenges, one of the most comprehensive field studies related to corrosion ever reported in the literature was carried out by Rasheeduzzafar [3–6]. Forty two concrete framed structures were carefully chosen such that all of them had two common characteristics — age and in-service exposure. The structures studied were thus all built during the period 1960–64 — which gave the opportunity for the analysis to be carried out with a high degree of reliability, and it was possible to isolate and establish the effects of some of the major variables on concrete deterioration. Such attention to detail and consideration of minute details without losing sight of the global nature of the issue concerned was typical of the work of Rasheeduzzafar, and speaks of the high and distinctive excellence of thinking that permeated all his research.

The techniques employed in studies of this nature reflect in a way the unique ability and qualities of the researcher. In the field study reported above, the controlling features of the environment such as aggregate source, salt prevalence, and climatic conditions were interwoven into special causal factors such as cracking due to thermal movements, shrinkage and thermal gradients, sulfate attack, and corrosion of reinforcement in order to establish their interaction and interrelationship. To arrive at meaningful conclusions, Rasheeduzzafar combined field observations and field measurements with laboratory analysis of cored samples of concrete and steel, and utilized a wide range of destructive and non-destructive test techniques to correlate the influences of a wide range of parameters such as areas of spalling, loss of metal rebar corrosion, crack widths, concrete cover, chloride content, electrical resistivity of concrete, depth of carbonation, and concrete quality. This was a mammoth contribution and an outstanding milestone in our understanding of the complex interrelation between these parameters, and it enabled Rasheeduzzafar to isolate parameters and establish the variations of metal loss, for example, with chloride content, concrete cover, quality of concrete as determined by the 30 min water absorption test, and the electrical resistivity of concrete. It is through these meticulous, detailed, and thorough studies that Rasheeduzzafar showed that the Arabian Gulf seaboard constitutes one of the most aggressive environments for concrete durability in the world. The chloride accumulation in the Gulf concrete, for example, ranged from about 0.5 kg/m^3 in uncracked concrete to about 3 kg/m^3 in severely spalled structural elements compared to about 1.15 to 1.9 kg/m^3 in bridge decks in the United States which have posed serious serviceability problems arising from deicing salt applications. It was only in isolated cases such as piling subject to 28 years of continual exposure to sea water that quantities of salt accumulation found in the United States reached values comparable to those in the Gulf. This ties up with the fact that the chloride content of sea water in the Arabian Gulf is about 1.6 to 2 times that of the Mediterranean or the Atlantic. These considerations led Rasheeduzzafar to postulate threshold chloride levels related to concrete cover for the onset of corrosion in the Gulf area. Identifying and defining the controlling factors of corrosion — concrete quality, concrete cover, soluble chloride content, and electrical conductance characteristics — Rasheeduzzafar has given the clear message to engineers, designers, and concrete specialists, and indicated the unambiguous route to quality concrete construction and long term freedom from steel corrosion [7, 8].

Experience with the performance of concrete structures all over the world has taught us that due to the higher alkaline aqueous phase contained in the pore structure of concrete, uncarbonated concrete in a chloride-free environment will show a long and durable service life because of the intrinsic protection against corrosion given to steel embedded in it. However, the chemical composition of the cement has a decisive influence on concrete's durability performance, particularly in the aggressive Gulf environment. It is in this respect that Rasheeduzzafar made another of his outstanding and far-reaching contributions to enhance our understanding of concrete science, and the deep-rooted and complex implications of the role of some of the major constituents of the cement matrix [9–14].

For a long time, the practice of the construction industry in the Gulf countries has been the exclusive and indiscriminate use of Type V cement, with usually a very low C_3A content, generally less than 3%. The penetrating research of Rasheeduzzafar has identified and characterized clearly and critically through laboratory and field exposure tests, the role of calcium silicates and calcium aluminates in portland cement and their influence on reinforcement corrosion and sulfate resistance [9–14]. These results show significantly better performance of Type I over Type V cement against rebar corrosion, and the need to specify the use of Type I cement instead of Type V cement in the construction of reinforced concrete superstructures, where corrosion of reinforcement and not the sulfate attack is the predominant cause for deterioration.

This unique research effort of Rasheeduzzafar has also shown that even some of the recommendations of bodies like CIRIA should be treated with caution [15]. This refers to the use of Type II cement, with a maximum C_3A content of 8% to take care simultaneously of the sulfate attack and chloride-induced rebar corrosion in the construction of substructures such as foundations. These substructures had posed a much more difficult problem in the Gulf area than superstructures such as bridge decks because of the concomitant presence of high chloride and sulfate concentrations in soils and ground water. Many foundations had thus been found to be suffering from both sulfate attack and chloride-induced rebar corrosion. The use of Type V cements does usually provide adequate protection against sulfate attack in such situations, but it is ineffective against chlorides as it fails to effectively remove free chlorides. One of the major conclusions of Rasheeduzzafar's comprehensive research in this area is that the available C_3A in type V cements will not be adequate to remove chlorides that permeate foundation concrete through the ingress and seepage of chloride-contaminated ground water. Thus, Type I cement with C_3A contents of the order of 12–14% will be significantly more effective in chloride removal and counteracting the effects on corrosion than concrete made with Type V cement, with a maximum of 5% of C_3A.

Rasheeduzzafar has clarified more firmly and reliably than many other researchers the mechanisms of deterioration of concrete in sulfate-bearing soils and ground waters in the Gulf area. This research has identified two major deterioration processes, namely, (*i*) the reaction between sulfate ions and the hydration products of C_3A resulting in expansion and cracking due to the formation of ettringite, and (*ii*) the reaction of $Ca(OH)_2$ with sulfate ions resulting in its conversion to gypsum and the consequent softening of concrete. All sulfate solutions tend to be somewhat acidic in nature. This second type of attack becomes important on prolonged exposure to acidic conditions, and can thus cause significant deterioration even in concretes with low C_3A cements. The extensive research on sulfate attack by Rasheeduzzafar shows that in addition to the C_3A content, the ratio of C_3S/C_2S in portland cement also has a significant effect in determining sulfate resistance.

In many countries, including the Gulf area, the demand for higher rates of strength development at early ages dominates the interests of the local cement industry in fixing cement composition. In many modern cements this is usually achieved by keeping the C_3S/C_2S ratio high. The Arabian Gulf region is no exception to this, and a sizeable proportion of cement produced in the area has high C_3S and low C_2S contents. To Rasheeduzzafar goes the credit for having brought to the notice of the construction industry the effect of a high C_3S/C_2S ratio and the role of gypsum on the durability performance of concrete against sulfate attack. Both Types of I and V cements with a higher ratio of silicates liberate more calcium hydroxide on hydration and consequently precipitate higher amounts of gypsum when exposed to sulfate solutions. The presence of gypsum in the hardened concrete causes a retrogression of strength and this can occur in Type I cement with C_3A content of 9–12% as well as in Type V cement with low C_3A of 2%, but both with a high C_3S/C_2S ratio of about 5.3 to 7.9. There is thus the need for specifications to limit the maximum permissible C_3S content in cements from the standpoint of durability to sulfate attack. The use of pozzolans ensures the removal of excess calcium hydroxide from the hydrated cement paste, and this explains the rationale behind the recommendation for their use to increase durability against sulfate attack [14].

The consistent beneficial effect of C_3A content in cement as indicated by the time to initiation of corrosion was also very systematically investigated through laboratory accelerated corrosion tests and field exposure tests. However, Rasheeduzzafar also recognized that as the chloride content of the concrete is increased, the performance differential between the two types of cements is progressively reduced. It is this interactive effect of higher chloride complexing ability and reduced chloride ion diffusivity of high C_3A cement that Rasheeduzzafar has highlighted and emphasized in obtaining better performance of such cements in terms of corrosion protection of the reinforcing steel in concrete.

If one were to identify the major areas where Rasheeduzzafar has significantly enhanced our understanding of concrete science and concrete technology, and shown the way forward to the means of better quality construction and long term durability in aggressive environments, the influence of cement composition, the effectiveness of different types of steel reinforcing bars, and the role of blended cements take pride of place [16–22]. In a short article such as this it is impossible to do justice to all the innovative ideas and concepts that he developed through research, keeping very much in mind the need to better the quality of construction and their durability in the Gulf environment. That he was a giant amongst giants in his technical, scientific, and research expertise is unquestioned and beyond dispute, but one quality that overrides all the technical excellence, and perhaps endows it with a high quality and exceptional value, is his humaneness and humility. In this respect he was a giant amongst pygmies. It was a well known poet who once said "the evil that men do lives after them". We can add that technical excellence adorned with qualities of humility and humaneness, will live forever and always be appreciated and admired by generations of young men and women.

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