Role of aluminium in constructional engineering

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SYNOPSIS

In this paper, applications of aluminium have been outlined emphasising the nature of components which need to be further developed and exploited to suit the conditions in this country. In dealing with these applications, the author sets out the basic parameters of a good constructional material and shows how they fit this light metal in terms of its physical, mechanical and engineering properties. The economics of using aluminium in constructional engineering has been discussed and comparisons made with conventional materials like steel.

Brief descriptions are also given of important structures built in aluminium to indicate its versatility. The paper concludes with some suggestions for this light metal and for creating a wider market in this country.

ALUMINIUM as is known today was first evolved simultaneously by Paul L. T. Heroult in France and Charles Martin Hall in Oberlin, USA, 82 years ago. Some years back the Italian journal, 'Alluminio' reported in its January 1961 issue, that a Chinese publication claimed that aluminium was found alloyed with copper and silver in fragments of a metal belt found in the tomb of Ts'in dynasty in Kiangsu province of Eastern China between 3rd and 6th century A. D. Under chemical and spectroscopic analysis further evidence would result in a reorientation of concepts of its origin leading to a trail much earlier than hitherto suppposed in the evolution of this light metal.

As far as extant records indicate, aluminium was first used in construction in 1884 in the form of a small pyramid weighing 2 835 kg as a capping to Washington Monument in USA. In 1897 the semi-cupola roof of the church of St. Gioacchino in Rome was built in aluminium, while in 1900 an extensive roofing area was put up in aluminium sheets in the Administrative Offices of the Government of New South Wales, Australia. In this country the aluminium industry started around the turn of this century. However, the first use of this metal was not made until the early thirities, when a beginning was made in the manufacture of utensils and a small industry built up. By 1965 the aluminium industry had assumed sizeable proportions and its production reached 69 000 tonnes. As much as 33 000 tonnes had to be imported since the consumption was over 102 000 tonnes. Today the total installed capacity is 108 000 tonnes against which the demand is around 150 000 tonnes, necessitating further imports.

Ironical situation

At present aluminium is consumed in a few major industries as shown below in per cent of total consumption:

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Electrical cables and electrical industry	50	per cent
Utensils and domestic industry	20	,,
Transport industries	10	,,
Packaging industry	8	,,
Building, architecture, construction and hardware	5	,,
Miscellaneous	7	,,
	100	per cent

It will be seen from this breakup that aluminium is used to the highest extent in cable and electrical industries and the lowest in construction. This situation is very ironical because the construction industry with its very large financial outlay should be the one to utilise this light metal to the maximum possible extent. In USA, Norway and Switzerland, more than 25 per cent of the total production of aluminium is used in building and construction industry. There is no reason why in India, the use of aluminium in this fabulous industry should not step up to this figure especially since the country will be spending large amounts on various construction projects. The total public and private sector outlay in India in the Fourth Five-Year Plan is around Rs. 23 000 crores, out of which the construction outlay

TABLE I Construction outlay in the fourth five-year plan

Items of work	Public Sector Rs in crores	Private Sector Rs in crores
Housing and general construction	550	1 450
Buildings for road, rail and sea transport, communications and tourism	1 960	550
Structures for power generation, transmission, distribution and rural electrification.	1 050	—
Construction and warehousing needs of agriculture, forestry, animal husbandry, dairying, fisheries, etc.	960	300
Irrigation and flood construction	850	—
Structures for small and large industries	850	700
Educational buildings	250	20
Buildings for scientific research	30	—
Buildings for water supply and sanitation works	520	—
Construction connected with welfare of backward classes	50	—
Construction connected with social welfare	20	—
Buildings for craft training and labour welfare	30	—
Miscellaneous development works for rural programmes	100	—
Construction under revenue budget	600	—
Total Rs	7 820/-	3 020/-
Grand Total Rs	10 840/-	

will be Rs. 10 480 crores subdivided under various heads as indicated in Table I. It can be easily realised that since each of these items requires constructional activity to be undertaken in some form or the other as in buildings, residential quarters, offices, power stations, pylons, schools, hospitals, bridges and culverts, the necessity of using constructional materials efficiently, effectively and economically, becomes imperative. It is estimated that in this outlay, some 5 million tonnes of steel will be required for which 50 per cent represent light structures for factories, roof trusses and the like. It is here that steel can be advantageously replaced by aluminium by utilising its characteristic properties like low density, high strength and excellent corrosion resistance.

Parameters for adaptability

A good constructional engineering material should possess durability, lightness, good strength, low maintenance and good thermal and acoustic insulation. The material must also be easy to fabricate, should be locally available, have good aesthetic appearance and should be comparatively economical. While no single constructional material can satisfy all these parameters, aluminium comes up very near to them. A typical set of physical and engineering properties of this metal is given in Table II.

Basically aluminium is white in colour, light in weight and has a density of 2·8 g/cc. In comparison it has 1/3 the weight of zinc, tin and steel; 2/7 of copper; 1/4 of lead; 4/5 of Plaster of Paris and has practically the same weight as marble, basalt, mica, glass and emerald. It is about 1·25 times heavier than concrete, 1·5 times heavier than bricks, and has nearly three times the weight of timber and rubber and ten times the weight of cork and wool felt. Its tensile strength in unalloyed form is as low as 5 kg/mm². This can be increased to over 60 kg/mm² when alloyed with other metals. Aluminium has a thermal conductivity more than three times that of steel and nickel; twice that of zinc; one and a half times that of magnesium; half of silver and 45 per cent of copper. Its electrical conductivity is 3·5 times that of steel and nickel; twice that of zinc; 58 per cent of silver and 62 per cent of copper. Aluminium has a thermal expansion about the same as melamine formaldeheyde laminate, rubber phenolics, tin and zinc;

TABLE II A typical set of physical and engineering properties of aluminium

Density	2·8 g/cc
Modulus of elasticity	7030 kg/mm²
Bulk modulus	7734 kg/mm²
Modulus of rigidity	2670 kg/mm²
Poisson's ratio	0·33
Proof stress 0·1 per cent (HV 30 alloy)	22 kg/mm²
Ultimate tensile stress (HV 30 alloy)	27 kg/mm²
Elongation	7 per cent
Thermal conductivity	0·50 cal/cm²/cm/°C/sec.
Coefficient of thermal expansion	0·0000236 in/in/°C
Notch strength	exceeds 10 mkg/cm²
Casting contraction	13 mm/meter
Relative power required for machining	1/4 of brass & cast iron 1/9 of mild steel 1/13 of nickel steel
Refractive index	1·48 at 6570°A
Mean specific heat	0·24 cal/gm/°C
Acoustic velocity	5200m/sec
Heat of vaporisation	1980 – 2030 cal/gm
Melting point	660°C
Boiling point at 99·5 per cent purity	2270°C
Electrical resistivity @20°C	2·65 microhms/cm³
Temperature coefficient of resistivity @20°C	0·00429 ohm/°C
Photoelectric emission	4·2 volts
Thermal absorption cross section	0·23 Barns
Half life of induced activity	1·4± 0·1 Barns
Lattice constant	4·046 cm
Atomic weight	26·98
Atomic volume	10·00
Radius of nucleus Al^{27}	$4{\cdot}6\times10^{-13}$cm
Shielding thickness @ 52 meV	1·15 cm
@ 100 meV	3·89 cm
@ 500 meV	55·5 cm
Heat of combustion in oxygen	7·41 kcal/g of fuel
Tensile strength of alumina whisker	15470 kg/cm²

double that of steel and concrete ; nearly three times that of glass and six times that of timber, tungsten and molybdenum.

The high strength and low density of the metal enables it to be used in stress carrying components like beams, columns, roof trusses, domes and cantilever members with lower overall weight. Its low elastic modulus needs to be carefully considered since it produces elastic instability in long and slender members, although at the same time this characteristic enables it to be used effectively in impact resisting structures very efficiently. Aluminium is also non-toxic, non-magnetic and non-sparking, while its corrosion resistance is very high. It has a fairly low melting point and is soft enough to undergo easy fabrication by forging, rolling or extrusion. Experiments indicate that in desert regions the surface remains absolutely intact as against a corrosion rate of 0·13 microns per annum for copper and 0·025 for zinc. Even in heavy industrial environments where copper and zinc wear away at 0·12 and 0·48 microns per annum respectively, aluminium corrodes just 0·079 microns.

Human comfort trends

In a tropical country like India, a good constructional material has to satisfy the basic norms of human comfort like thermal insulation and reflectivity to as great an extent as possible. While several mechanical means are available for keeping the inside of a building cool and comfortable, like fans and air conditioning, the simplest and cheapest are the natural methods which incorporate insulation within the fabric of the structure itself. In this context the high reflectivity of aluminium for white light and its low emissivity are important factors governing the low rate of transfer of solar radiation. An absolute black body has an emissivity of 1·0 and all other surfaces have an emissivity less than one. In this connection it is worthwhile noting that aluminium has as low an emissivity as 0·02 to 0·04 as against 0·85 of white-wash, concrete or stone surface.

The fact that aluminium roofs keep the inside of rooms cool is attributable to its comparatively low thermal transmittance coefficient namely 3·9 kCal/m^2 hr.°C as against 5·86 to 6·0 for corrugated asbestos or galvanised iron sheeting ; 2·44 to 3·0 for concrete flat roof and 1·5 for a 28 cm single cavity brick wall. A thick embossed aluminium foil laminate is ideal for tropical countries when used in roofing. The economy of a foil lies in its inherent properties of lightness, impermeability and durability. For a given weight of thickness aluminium foil covers a very large area. Thus a 0·009 mm aluminium foil covers 8·5 sq.m/kg as against only 3·2 sq.m/kg for a tin foil of equal thickness.

Roofing

Among the various roofing materials commonly used, aluminium is comparatively the lightest as can be seen from Table III. In fact as far as asbestos cement sheets are concerned, aluminium is not only lighter than these sheets, but even on a direct cost basis, competes with them, with the added advantage that unlike cement sheets, there is absolutely no wastage due to breakage either in transit or during fixing.

TABLE III Comparative weights and prices of roofing materials

Material		Weight in kg/sq. m	Cost in Rs/sq.m
Corrugated aluminium sheets	20 G	2·8	16
	22 G	2·2	13/50
	24 G	1·7	11/50
Everest crownit asbestos Cement corrugated sheets		15·2	13
Corrugated galvanised iron sheets	22 G	9·76	16
Zinc sheets	12 G	4·58	25
	14 G	5·81	32
	16 G	7·61	42
(Gauge numbers of zinc sheets run opposite to conventional numbering)			
Copper sheets	24 G	6·34	108
Reinforced concrete slab 76mm thick		176	88
Reinforced concrete shell roofing, 38 mm thick		88	70

In India plain and corrugated aluminium sheets have been used fairly extensively in roofing various structures like Hindustan Machine Tools Factory, Bangalore ; Electrical Machine Corp., factory near Calcutta ; Tea Garden labour dwellings and T. B. Hospital, Assam and beach huts in Madras. In the Heavy Electricals factory at Bhopal the use of aluminium in several roofing systems resulted in a saving of some 700 tonnes of steel and a financial economy of nearly Rs 13 lakhs.

In addition to roofing sheets aluminium can be used in roof trusses. Although utilised extensively in western countries, this application does not appear to have been recognised very seriously in India. A complete roof truss with aluminium members and aluminium sheeting becomes extremely light and effects economies in weight to a considerable extent on the whole structure. Roof trusses spanning 4 m to 25 m have no more than 1/4th to 1/5th of the weight of a similiar steel truss. In fact as the span increases the savings in weight become still greater. Thus shallow dome roofs which can be built up to 180 m diameter would weigh only about 1/8th the weight of a steel dome. An 80 per cent saving in weight was achieved by ingenious design and skilful use of aluminium in a roof structure on the harbour front at Antwerp, Belgium. Using medium strength aluminium alloys, latticed beams with mild steel girder stanchions and haunches for pinned base ; rigid haunch portal frames at 19·5 m centres ; and aluminium alloy purlins at 2 m centres, the structure not only saved steel but proved to be less expensive than either a fully steel or timber structure. With corrugated aluminium sheeting, the roof weighs less than 10 kg/m^2 (2 psf), a remarkably low figure for such spans. The entire structure weighs 132 tons and the cladding 77 tons, which is estimated to be approximately 1/7th in weight of an equivalent steel structure.

Long span structures

Aluminium is an expensive light metal and as such has to be designed and utilised in such a manner that every gram of its volume is stressed to its maximum possible extent as has been done by aeronautical engineers. Like the aircraft, structural dead loads and erection and maintenance costs play a significant part in determining the ideal material for bridges. In moveable structures like lift and bascule bridges, aluminium is the material for use, for here lightness results in economies in counter weights, the machinery which runs the bridge and in the foundations. It is difficult to state in general at what spans and at what loadings aluminium can directly compete with steel, as a number of variables enter into design considerations. However, from a study undertaken by the author it can be said that the limit of spans is not very high. Assuming the use of an alloy having an ultimate tensile strength of 44 kg/mm^2 and a 0·1 per cent proof stress of 37·8 kg/mm^2, it can be said that a bridge in aluminium can compete with an identically loaded steel bridge at spans from 36m and over for simple truss type design ; 45m for continuous or cantilever trusses and 76m for arch bridges. Here the normal cost of aluminium is assumed to be five times that of steel. By using unconventional designs like triangular trusses, space frames and monocoque construction the limit can be brought down still further. The 'Unistress' bridge evolved by an American engineer uses this latter principle. Essentially it is a semi-monocoque structure composed of triangular shaped beams bolted together edge-to-edge to form a roadway base. Each beam is a cell fabricated in the shop from aluminium sheet and stiffened inside with aluminium extrusions for maximum strength per weight of metal used. Because of this, one kg of aluminium in this bridge does the work of 6 kg of steel and has actually proved economical for spans over 20m.

Among the structures nowadays being vigorously investigated for long spans are 'Space Frames'. Offering highly aesthetic forms with substantial lightness, a space frame is a 3-dimensional system in which a large number of straight members are interconnected to form a regularly recurring pattern or lattice, like an octahedron. Here loads are very evenly distributed, reaction proceeds very fast, scaffolding is reduced to a minimum, the overall weight of the frame is very low and very large areas can be covered with ease. Space frames lend themselves ideally to aluminium, since extruded sections can be used for main members and sheeting for coverings. The author feels that the possibilities of use of such structures in India should be seriously investigated since they offer really economical solutions to problems associated with large span areas.

Public works construction

Constructional engineering does not limit itself to mere buildings but spreads its tentacles to other fields like public works, municipal and hydel engineering. Thus sewage installation plants have realised the excellent characteteristics of aluminium and put it to use in such items as doors, windows, floor gratings, tread plates, conduits, weir plates, sluice gates, collection and scum troughs and bar screens. While the initial installation cost may be high, the fact that no renewal and maintenance is required, results in an accumulation of savings over the years.

Nearly 70 per cent of India's population live on agriculture. A sound and efficient mode of irrigation through modern techniques is therefore very vital for the country. One of these techniques lies in using aluminium in various ways. Pipes and fittings in aluminium produce an overall lightness in handling which in turn can increase output of work and raise production. In India where the agriculturist has to depend on the vagaries of monsoon, sprinkler irrigation is an asset. In the Assam tea gardens and in Coorg, aluminium has been accepted for this type of irrigation. In sprinkler irrigation the spraying lines are built up from aluminium tubes provided with quick-acting aluminium couplings and take-off elbows with seals, which prevent leakage at the joints. Aluminium with its excellent corrosion resistance and good hygienic character is ideally suited for the bulk storage of grain like bajra, wheat, jowar and gram. A well designed and built aluminium bin can prevent these products from being destroyed by nature's enemies like the rice weevil, the grainborer, beetles and fungi. Because of the high reflectivity of the metal, the inside temperature of the dins is kept down to a minimum even in warm climates thereby eliminating the incidence of fermentation. Prefabricated aluminium bins appear to be slowly making inroads in village development blocks and their use should be spreading further once their advantages are realised.

In hydel works, aluminium pipes have been used in the west for well over six decades. Lightness is the main factor in their use, for they increase the overall productivity. Thus a 3m long pipe 100 mm in diameter as is used in irrigation can be easily handled by just one man ; with steel this becomes a difficult proposition. Aluminium pipes are light in weight, do not present any problems of corrosion on their internal surface and being very smooth permit the free flow of liquids. Thus the friction head lost in a new 100 mm pipe in which water at 22°C is flowing at a velocity of 1·5 m/sec, is just 2m per 100m pipe length. Further, aluminium pipes can be easily bent, shaped, beveled, grooved and threaded at site. The use of aluminium in mobile concrete mixers offers a substantial advantage over conventional mixers and requires to be investigated in India. In a typical 7 c.yd mixer the overall weight is reduced by 35 per cent, which means less power for hauling the plant or increased movement without extra cost. Among other fields where aluminium offers service to the construction engineer, are pylons, booms of cranes, shuttering for concrete, snow avalanche fences and tubular scaffolding.

Economic aspects

The production of aluminium is unusual because it combines within one industry a number of engineering operations. Obtaining bauxite involves the most advanced mining techniques, while preparation of pure alumina from bauxite is a large scale chemical engineering process. The vital part of obtaining cheap electrical power to produce the metal necessitates the setting up of giant civil engineering schemes and the application of latest advances in electrical and nuclear sciences. The smelting operation is an unusual technique in extractive metallurgy. Semi-fabrication of the metal incorporates advanced mechanical equipment and complex operating methods. Thus, by the time the finished metal is available to the constructional engineer in either rolled, cast, extruded or wire form, its price becomes very high and aluminium *per se* is regarded as an expensive metal. The comparatively high cost of aluminium in India as against world prices arises from the fact that the cost of electric power is higher in this country, while the metal is subjected to an unwarranted excise duty amounting to nearly 25 per cent of the basic price. No wonder Indian aluminium costs construction engineer an amount per tonne which is comparatively higher than the average cost in western countries and as such he shirks using the metal as freely as other conventional materials like steel, timber or reinforced concrete. Nonetheless aluminium does have inherent advantages like low density, good strength and absence of corrosion which should make it a useful material in spite of its high basic cost.

The final cost of a structure is made up of basic cost of the material itself, the cost of fabrication and erection, the cost of special treatment like painting or anodising, the cost of maintenance, the cost of transport and the cost recoverable from scrap. Aluminium requires hardly any painting or maintenance; its transport cost is very meagre due to its low density, while its scrap value compared to steel is very high. The major economic consideration therefore revolves round the four parameters: density of the metal; allowable stress; nature of loading; and type and cost of fabrication and erection. At current rates the author has found that the cost of aluminium including erection and fabrication in Rupees per kg is nearly five times that of steel, four times that of timber and twenty times that of prestressed concrete. On this basis and taking conventional values for working stresses it is found that for identical loading and span, aluminium is nearly two and a half times more expensive than steel, and more than three times as expensive as prestressed concrete. This however does not take into consideration the dead load of the structure itself, which becomes very predominant as the span increases. When such dead weight considerations are brought into the picture, the economics of using aluminium tend to swing in favour of the light metal. Under certain assumed loading condition, the author has found that when the dead load of the steel frame is about three times the live load of aluminium framing the cost of structures in either metal is the same. Here the complete fabrication and erection costs in aluminium are assumed to be seven times that of steel, and the ratio of allowable stress in steel to aluminium as 1·15. Thus when the dead load of the steel frame exceeds the value of three, aluminium framing becomes cheaper than steel. It must be realised that as more aluminium is used in construction works and experience gained, the fabrication and erection costs will no doubt be reduced from a figure of seven to about five in ratio. Further, as larger aluminium plants are set up the basic cost of the metal will also come down. Under such conditions, aluminium framing would easily compete with steel framing even for medium and short spans especially when corrosive environments or difficult foundation conditions are encountered. In fact in the field of roofing, aluminium offers the best all round value as can be seen from Table III.

In short aluminium offers the construction engineer a genuinely versatile material which can be utilised in a variety of forms. As the author has always been advocating it is very essential to inculcate a greater awareness about aluminium amongst laymen as well as technologists if the metal is to be increasingly utilised. The time is also ripe for setting up an independent and an authoritative information disseminating body to solve the problems faced by the aluminium industry. Such a body could be patterned on the lines of the Aluminium Federation, in UK, or Centre Technique de l'Aluminium, France, and could be made to act as a catalyst in spearheading the uses of aluminium on a wider and broader front.