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Portland cement concrete will continue to be the dominating construction material in the future. As with other industries, progress in concrete technology should necessarily take into account the widespread need for conserving resources and environment and for proper utilization of energy. Consequently, it can be expected that there will be major emphasis on the use of wastes and by-products in cement and concrete technology. Efforts will also be directed to use recycled materials such as demolished wastes from structures and slurry from ready-mix concrete operations.

Wastes can be used as raw material in cement clinker, admixtures in cement, or as aggregates in concrete. This Digest discusses the potential use of some wastes and by-products as concrete aggregates, an application that is particularly promising as 75% of concrete is composed of aggregates. The various materials examined include slags, wastes from power plants, reclaimed concrete, mining and quarrying wastes, colliery spoil, waste glass, incinerator residue, red mud, burnt clay, and sawdust. The use of these materials, however, is limited in that many are produced at great distances from the construction sites.

The waste materials that have the best potential are blast-furnace slag and fly-ash. They have desirable properties such as soundness, strength, shape, abrasion resistance and gradation.

Materials such as reclaimed concrete, waste glass, and sawdust should be considered for application after further research and developmental work. They are used to a limited extent and require some processing.

Many materials such as sludges and tailings have non-uniform characteristics and do not meet the standard requirements of good aggregates. Some of them must be dewatered before use, which adds to processing costs.

Slags

Blast-Furnace Slag -- Blast-furnace slag is formed when iron ore is converted to iron (called pig iron). The slag is then slowly cooled in the air to produce a crystalline, dense material known as "air-cooled slag," or rapidly discharged and treated with water jets to produce a lightweight material known as "foamed slag."

Air-cooled slag is suitable as an aggregate in concrete. A comparison of the compressive strengths of concrete made with blast-furnace slag aggregate, and that with gravel and crushed limestone shows that slag concrete is stronger. Slag fines may be used as a substitute for sand without any deleterious effect. Volume stability, good sulphate resistance, and corrosion resistance to chloride solutions make reinforced slag concrete suitable for many applications.

Only a small amount of *foamed slag* is produced compared to air-cooled slag. It finds application in the manufacture of lightweight concrete with a bulk density of 800 to 950 kg/m³. Foamed-slag concrete blocks are used both in load and non-load bearing walls. This concrete has high fire-resistance properties and about 75% of the thermal conductivity of other lightweight concretes.

Foamed slag in a pelletized form has been developed in Canada. Production of this type is claimed to contribute less to air pollution than does the normal process.

Steel slag -- This slag is formed by the removal of impurities from pig iron. Steel slags may be rich in phosphate or in calcium and contain metastable dicalcium silicate; hence they are used only as road fill. Steel slag is generally weathered in stockpiles for up to one year before use.

Other Metallurgical Slags -- The application of slag produced in the smelting of copper, zinc, lead, nickel and tin has yet to be explored fully. Zinc/lead slags have been examined for use as aggregates in asphaltic concrete. In cement concrete, these slags may produce an alkali-silicate reaction. They have also been suggested for use as fine aggregates in concrete. Air-cooled slag produced in the manufacture of phosphorous has been developed as aggregate for use in concrete.

By-Products from Power Plants

Several by-products are formed in the coal-burning process for the generation of electricity. In the older power stations using lump coal, a residue known as "furnace clinker" is produced. In modern plants, ground or pulverized coal is used for steam generation. Small particles carried upwards by the combustion gases are subjected to electrostatic precipitation or collected by other means. These particles are termed "fly-ash" or "pulverized fuel ash." Some of the ash particles also clinker together and fall to the bottom of the furnace, hence the name "furnace bottom ash." In furnaces at higher temperatures, a molten residue known as "boiler slag" is also produced.

Furnace Clinker -- A substantial amount of unburnt coal and other impurities is contained in furnace clinker. It is used mainly in the manufacture of concrete blocks. Because furnace clinker contains sulphates and chlorides, it is not recommended for producing reinforced concrete. This material may become more scarce as the older power stations convert to using pulverized coal.

Furnace-Bottom Ash -- This residue forms approximately 2.5% of the total ash production. The availability of ash is expected to increase as more coal is utilized. The chemical analysis of American furnace-bottom ash is similar to that of fly-ash, except that it is higher in alkalis and sulphates. Furnace-bottom ash and boiler slag may be used as lightweight aggregates for making concrete blocks.

Fly Ash -- Although fly-ash is suitable for production as a lightweight aggregate, it is used only in small amounts for this purpose. The advantage of fly-ash over other lightweight aggregates is that it promotes fuel efficiency because the carbon in the ash provides sufficient heat needed to evaporate the moisture in the pellets and bring the pellets to the sintering temperature.

Initially, fly-ash is mixed with water and formed into pellets either in a revolving cone disc or drum or by extrusion. It has been found that a small addition of alkali produces a pellet with better resistance to mechanical and thermal shocks. In the sintering by travelling-grate process, the temperature reaches about 1150 to 1200°C and causes the small particles of fly-ash to fuse and form a cake. The cake is then broken to obtain discrete pellets. Concretes made with these aggregates possess 28-day compressive strengths of the order of 40 MN/m² and densities of about 1100 to 1800 kg/m³. As these aggregates have good shape, strength and moderate water absorption, they are suitable for producing lightweight concrete blocks and structural lightweight concrete.

The suitability of fly-ash for the pelletization and sintering processes is difficult to predict because many physico-chemical factors are involved. Generally aggregates of suitable quality can be obtained by keeping the carbon content between 3 and 10%. Excessive amounts of iron cause staining of the concrete.

Reclaimed Concrete

Concrete accounts for nearly 75% by weight of all construction materials and it follows that it should also account for the major percentage of demolished wastes. Millions of tons of concrete debris are also generated by natural disasters. Depletion of normal aggregate sources, stricter environmental laws and waste disposal problems are factors that make the use of reclaimed concrete an attractive proposition. Concrete pavement debris is already used in the sub-base for new pavements.

Compressive strength and modulus of elasticity of concrete containing recycled aggregate are lower than in concrete containing normal aggregate. The differences are greater at lower water:cement ratios. Substitution of sand for the fines of recycled concrete aggregates does not result in improved strengths. Concrete using fines from recycled concrete requires a higher water:cement ratio. This is expected because of the presence of higher amounts of hydrated cement particles. The use of water-reducing agents and higher cement contents would result in higher strengths.

The drying-shrinkage of concrete made with recycled concrete is greater by 10 to 30% compared to the control concrete. Shrinkage values depend on the total surface area; in the recycled aggregate the surface area is expected to be high because of the presence of cement paste.

The freeze-thaw durability of concrete containing recycled concrete aggregate is similar to that of the control containing normal aggregates.

Most of the reported work has been done on uncontaminated concrete. The only impurity that has been studied is sulphate in combination with crushed concrete. Concrete rubble will be contaminated by impurities present within the concrete and by other materials of the building structure. Many factors may contribute to the low strength development in recycled concrete systems. The economics, durability, creep, wetting expansion and other related properties must be studied more extensively before recycled concrete gains wider acceptance.

Mining and Quarrying Wastes

Large amounts of wastes are produced in mining and quarrying operations. Mineral mining wastes are termed "waste rock" or "mill tailings." Generally, these wastes have not as yet found any significant application because they are produced at locations far removed from populated areas. Some of the possible uses of these wastes are: the manufacture of bricks, lightweight aggregates and autoclaved concrete blocks. One of the problems in the use of these wastes is the large variability in their composition.

Miscellaneous Wastes

Colliery Spoil -- In coal operations, about one half of the material is separated and discarded as colliery shale. Most of this spoil finds application as fill in road embankments. It can also be used to produce lightweight concrete aggregate. The temperature to which the spoil is fired to produce bloating or expansion should be controlled such that the gases from the clay or any other material are entrapped within the softening pellet. All spoils may not bloat and, hence, preliminary experiments should be carried out to evaluate the bloatability of a particular colliery spoil. Dense aggregates may also be produced by controlled heat treatments.

Waste Glass -- Millions of tons of refuse glass are generated annually. In general, the strength of concrete containing glass is lower than that with gravel aggregate. Strengths are particularly low when high alkali cement is used. Flexural strengths show a similar trend. Replacement of cement with about 20 to 30% fly-ash is effective in controlling the large retrogression of strength.

Waste glass is susceptible to alkali-aggregate reaction. Large expansion occurs in the presence of high alkali cement, which explains the low strengths in glass-based concrete. For example, compared to an expansion of 0.018% at 12 months for gravel-concrete, the glass-concrete may exhibit an expansion of about 0.3%.

Waste glass can also be used to make lightweight aggregates. Lightweight expanded aggregate of density 528 kg/m^3 been produced by pelletizing a mixture of ground waste glass, clay and sodium silicate and heating to about 850°C. Concrete made with this aggregate yields a compressive strength of about 17 MPa after curing in steam for 28 days.

There are several problems associated with the use of waste glass that must be solved before it can be used economically. The glass is of variable composition, often contaminated with labels, dirt and other substances that must be removed. Crushing of glass produces an elongated particle shape, and the physical and chemical nature of its surface do not make it suitable as an aggregate in concrete. Sugar-contaminated glass should be cleaned well to prevent excessive retardation influences on concrete.

Incinerator Residue -- The incineration of domestic and industrial refuse produces a large amount of solid residue. The chemical composition of the residue changes widely depending on how the initial material is processed and may also change with the season. The major problem in utilizing this residue in the production of concrete is the presence of some deleterious materials: aluminium causes expansion due to the evolution of hydrogen; ferrous metal causes staining of concrete; and soluble lead and zinc salts interfere with the setting of cement. The presence of glass will lead to alkali-aggregate expansion.

Red Mud -- Red mud is a waste product resulting from the extraction of alumina from bauxite ore. It is sufficiently plastic to be moulded into balls. Firing at about 1260 to 1310°C produces a strong dense aggregate with which concrete of suitable strengths can be obtained.

Production of synthetic lightweight aggregate from red mud may present problems because red mud melts only at high temperatures, has a narrow softening range, and the gases generated during softening may not be sufficient to cause bloating; several additions have been tried without success. In a few cases, lightweight aggregates have been produced with additives such as fly-ash, blast-furnace slag or pumice.

Burnt Clay -- Depending on the method of firing and handling in the manufacture of bricks, a certain percentage is broken, underburnt or overburnt. Crushed, well-burnt brick makes a suitable aggregate for the manufacture of concrete blocks. In such concretes the permeability will be higher, and if the brick contains soluble salts efflorescence and corrosion in the reinforced concrete may occur. One of the advantages of concrete containing burnt clay is that it has greater fire resistance than concrete made with natural gravel aggregates.

Sawdust -- Sawdust concrete is used to a limited extent because it possesses very low strengths. Typically, 1:2 and 1:6 mixes (cement:sawdust by volume) yield a 7-day compressive strength of 7.5 MPa and 0.75 MPa, respectively. The addition of sand can improve strength. Sawdust concrete has a good insulation value, resiliency, low thermal conductivity, and can be sawed and nailed. But in locations where water accumulates or is in constant contact with it, sawdust concrete can absorb large amounts of water and expand. Sawdust must be pre-soaked to remove soluble matter before use in concrete. Concrete containing large amounts of sawdust is flammable. Sawdust from red oak, Douglas fir, cottonwood, maple, birch or red cedar makes very low-strength concretes, whereas that from spruce or Norway pine yields concretes of acceptable properties.

Conclusions

Deposits of natural sand, gravel, and stone, especially those located close to major urban centres, may get depleted or become costly owing to transportation costs and environmental restrictions. There are several types of wastes and by-products that can substitute as aggregates. Blast-furnace slags and fly-ash are by products that are already exploited commercially. Over-all economics and suitability of waste materials will dictate their application. Variability of the physical and chemical characteristics, and availability at locations far removed from populated areas may inhibit the widespread use of many types of wastes. Future work will have to be directed to a study of the long-term durability of concretes containing these materials. Attempts will have to be made to devise simple treatments and modify manufacturing methods so that more waste products become by-products and their use becomes commercially feasible.