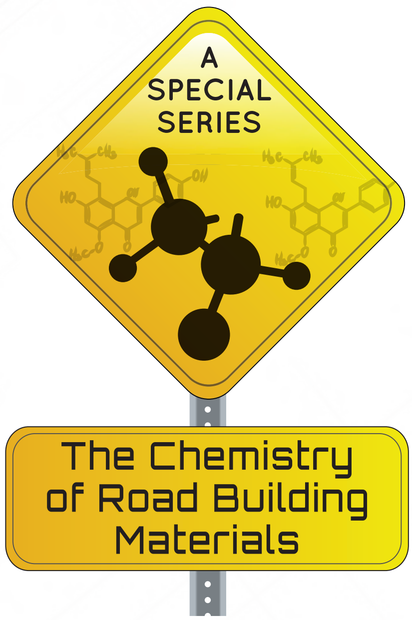
by Tom Kuennen, *Contributing Editor*



On the Face of It

Aggregate performance depends on its surface

The higher-performing bituminous and portland cement concrete mixes of today are becoming more complex, and to ensure performance, more scrutiny is being given to the chemistry and composition of the aggregates which go into those mixes.

And a growing amount of that scrutiny is aimed at the surface of a piece of aggregate, because it's at that interface – where rock meets liquid asphalt or cement paste – that pavements can succeed or fail.

Aggregates are the component of a composite material – such as bituminous asphalt or portland cement concrete – which resists compressive stress. Aggregates in asphalt or concrete will have a wide variety of sizes, from coarse material to sand, bound in a matrix by a cementing medium.

The degree of porosity of the surface of a particle of aggregate can make or break a mix. The film of liquid asphalt that enrobes a piece of aggregate bonds better if it can be absorbed into the surface of the rock.

If asphalt binder loses its grip on aggregate or "strips", and the pavement begins to fall apart, it may be because too much moisture was present on the surface of the aggregate when mixed. If too much dust was present on the surface of coarse or fine aggregate particles, the liquid asphalt will mix with the dust and not bond very well with the aggregate, and stripping also will occur.

"Physical and chemical properties of aggregates at the micro scale strongly impact the adhesive bond (strength and durability) between bitumen and aggregate," write Amit Bhasin and Dallas Little, Texas Transportation Institute (TTI), in their paper, Characterizing Surface Properties of Aggregates Used in Hot Mix Asphalt, published by ICAR, the International Center for Aggregates Research "These properties include surface free energy, chemical interaction potential, and specific surface area."

The surface free energy of aggregates – a manifestation of material surface physical chemistry characteristics – is one way aggregates can be classified as to future performance. Surface free energy of aggregates can impact the interface between the asphalt and the aggregate (adhesive fracture), or fracture within the asphalt binder or mastic itself (cohesive facture), researchers at Texas A&M University's TTI say.

"The intrinsic surface forces that take part in fundamental adhesion can be attributed to the fact that atoms and molecules in that region usually possess reactivity significantly different from units in the bulk," say Arno Hefer and Dallas Little in their ICAR report, Adhesion in Bitumen-Aggregate Systems and Quantificaiton of the Effects of Water on the Adhesive Bond.

"In the bulk phase, a unit experiences a uniform force field due to interaction with neighboring units," Hefer and Little write. "However, if a surface is created by dividing the bulk phase, the forces acting on the unit at the new surface are no longer uniform. Due to the missing interactions, the units are in an energetically unfavorable condition, i.e. the total free energy of the system increased. This increase in energy is termed the 'surface free energy' or more accurately the 'excess surface free energy' ... [s]imple, efficient and reliable measurement of surface energy is an important consideration for implementation of this technology."

For asphalt pavements, the goal is to analyze the physiochemistry of aggregates and binder to select combinations of liquid asphalt and aggregates that are more resistant to moisture damage, will perform best with modifiers and other additives, and whose performance can be predicted.

In portland cement concrete, alkali-silica reaction (ASR) begins at the cement paste/aggregate interface. ASR is a chemical reaction that occurs between alkalis contributed

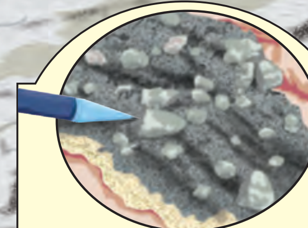
April	May	June	July	August	September	October
THE CHEMISTRY OF ASPHALT MODIFIERS	THE CHEMISTRY OF CONCRETE ADMIXTURES	THE CHEMISTRY OF ASPHALT EMULSIONS	**THE CHEMISTRY OF AGGREGATES**	THE CHEMISTRY OF LOW-ENERGY MIXES	THE CHEMISTRY OF RECYCLED/ RECLAIMED MATERIALS	THE CHEMISTRY OF PAVEMENT FORENSICS

Crushed stone (shown) and sand and gravel constitute the major types of construction aggregates. Crushed stone is an angular rock of plutonic or sedimentary origin, crushed and screened to spec in quarries, while gravel has a more rounded shape, produced by weathering and erosion (unless crushed), and is extracted from fluvial or glacial deposits or "pits". Sand also is extracted from pits but manufactured sand is produced in quarries

Image Credit: Bill Bradley

Lightweight aggregates comprise a ceramic material produced by expanding and vitrifying select shales, clays and slates in a rotary kiln. This pyroprocessing produces an aggregate that is structurally strong, durable, environmentally inert and low in density

Image Credit: Expanded Shale, Clay and Slate Institute



The condition of an aggregate impacts its performance. Dusty aggregates – in which aggregate dust coats either coarse or fine aggregate – can contribute to stripping in asphalt pavements, as the liquid asphalt binder coats the dust and not the aggregate surface. But moisture used to clean the aggregate can cause stripping as well

Image Credit: Caltrans

Aggregates are the component of a composite material – such as bituminous asphalt or portland cement concrete – which resists compressive stress. Aggregates in asphalt or concrete will have a wide variety of sizes, from coarse material to sand, bound in a matrix by a cementing medium

ASR is a chemical reaction that occurs between alkalis contributed primarily by cement, and a reactive form of silica from reactive aggregate, which form an alkali/silica gel. Under the right conditions – particularly enough available moisture – the gel will expand and produce stresses and damage in the concrete

Image Credit: Portland Cement Association

Synthetic aggregates can be made from recycled materials. For example, in the SYNAG process, coal combustion fly ash is cold-bonded chemically to produce a hardened product that can be crushed and sized for construction applications, with properties specified by ASTM and AASHTO. The chemistry of reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA) as construction aggregates will be discussed in September

Image Credit: Western Research Institute

Piezoceramic-based devices – smart aggregates – someday may monitor dynamic seismic response and perform structural health monitoring for large-scale concrete structures

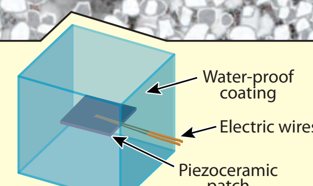


Image Credit: Gu, Moslehy, Sanders, Song and Mo primarily by cement, and a reactive form of silica from reactive aggregate, which form an alkali/silica gel. Under the right conditions – particularly enough available moisture – the gel will expand and produce stresses and damage in the concrete.

Construction Aggregates

Crushed stone and sand and gravel constitute the major types of construction aggregates. Crushed stone is an angular rock of plutonic or sedimentary origin, crushed and screened to spec in quarries, while gravel has a more rounded shape, produced by weathering and erosion (unless crushed), and is extracted from fluvial or glacial deposits or "pits". Sand also is extracted from pits but "manufactured sand" is produced in quarries.

Plutonic aggregates include the igneous rock granite, on the average by weight made up of 72 percent silica (SiO_2), 14.4 percent alumina (Al_2O_3), with the remainder oxides of potassium, sodium, calcium, iron and magnesium; and varieties of basalt, known widely as trap rock, on average made up of 45 to 55 percent silica, 14 percent or more alumina, and some 10 percent CaO, 5 to 12 percent MgO, and 5 to 14 percent FeO.

Sedimentary aggregates include limestone, made up almost entirely of the minerals calcite and aragonite, which are different crystal forms of calcium carbonate ($CaCO_3$); and dolomite, composed of calcium magnesium carbonate $CaMg(CO_3)_2$, in which magnesium replaces calcium in amounts over 50 percent. Lesser replacements result in a stone called dolomitic limestone. A useful sedimentary or evaporative stone for use on unpaved roads is the abrasive anhydrite, a hard variety of normally soft gypsum (calcium sulfate, $CaSO_4 \cdot 2H_2O$), but lacking the water component.

The popular image of a quarry is an open-cast site from which tombstones, countertops and other types of dimension stone are extracted. In reality dimension stone accounts for the barest fraction of stone in terms of raw tonnage; shot-and-crushed stone accounts for the vast portion of stone produced.

"After the blast, quarry material comes in size gradations unsuitable for product sale," said Florian Festge, president, W.S. Tyler, Inc. "To make a final product, producers must first break larger rocks into smaller ones and limit the appropriate top size. This process is conducted by crushing using a close side setting equal to the largest rock size desired in the final product. Crushing therefore provides the foundation for the proper sizing of aggregate stone."

As important as crushing is, the final product is refined by correct screening. "Screening is the separation of material by size," Festge told Better Roads. "Vibrating screens continuously convey and propel rocks into flight in order to allow for a comparison between rock size and screen opening once the material hits the screen again. Because of the significantly higher investments required into crushing equipment, producers often focus their attention solely to the crushing equipment, when in fact the determination of the product purity and quality – which is critical to the customer – is determined on the vibrating screen during the screening process. It's essential for any aggregate operation to place equal attention on both crushing and screening to obtain the highest product quality, as well as operating profit."

Premium Aggregates

In the meantime, the chemical/mineral makeup of each aggregate type lends varying degrees of compressive strengths, water content and skid resistance. In the past – due to the cost of shipping of aggregate – local road agencies had to be content with whatever aggregates were locally available. But since the advent of the Strategic Highway Research Program (1987-1993) and the resulting Superpave system of performance-graded liquid asphalts and mix designs, the higher costs of premium aggregates shipped in from out of state – along with stone processed to boost angularity – have been absorbed by state road agencies and ultimately, highway users.

"Crushed stone and crushed gravel are the major sources of most pavement aggregates," said Richard C. Meininger, P.E., highway research civil engineer at the Federal Highway Administration, and Steven J. Stokowski, P.G., aggregate technologist and petrographic laboratory expert with SES Group & Associates, LLC, in a presentation during the Transportation Research Board meeting in Washington, D.C., in January 2011.

"Their angular shapes perform well in applications where interparticle friction adds to pavement strength, such as granular bases and asphalt layers," Meininger and Stokowski said. "For portland cement concrete, natural sand, gravel, and crushed stone are widely used in pavements and structures as well. Natural sand, as the fine aggregate for concrete, is entrenched in highway agencies' specifications because its rounded shape contributes to concrete workability. Using crushed, angular, and manufactured fine aggregates in concrete, mortar, and grout applications is more difficult, but may be necessary in some areas."

That's how specs begin to favor premium aggregates. "To be useful to highway agencies, first and foremost, aggregates must be of a sufficient quality to meet both initial design needs and long-term, life-cycle performance objectives," Meininger and Stokowski said. "Industry decision-makers regularly consider alternative blends, recycled sources, and gradings, as well as other aggregates specified for the project designs. Developing specifications that allow more blending to meet performance objectives can help preserve premium aggregates for critical uses."

Classic asphalt mixes typically are made up of 94 to 96 percent aggregate and 4 to 6 percent asphalt cement, reports the National Asphalt Pavement Association (NAPA). And the Portland Cement Association (PCA) observes that portland cement concrete, by volume, will be composed of 60 to 75 percent aggregates (including sand), with 10 to 15 percent portland cement, and the remainder water.

The National Stone, Sand & Gravel Association (NSSGA) reports that, on average, every lane-mile of Interstate uses 38,000 tons of aggregate, compared to an average 400 tons of aggregate used for a new home.

Coarse aggregates generally are those pieces greater than 4.75 mm (0.19 in.), but usually between 3/8 and 1 1/2 inches in size. Fine aggregates are natural sand, or "manufactured" sand from a quarry, which pass the 3/8-in. sieve. Aggregates are "graded" according to their size, and a "gap-graded" aggregate mix – used more and more in high-performance pavements – is one that entirely leaves out certain unwanted gradations.

Aggregate properties or characteristics include their durability, their resistance to skids and abrasion, their ability to absorb water (absorption is critical in freeze-thaw resistance), their particle size, shape and texture, their grading, and the voids they provide in a mix of aggregate.

The properties of coarse and fine aggregates used in asphalt and PCC pavements and unbound base and subbase layers are very important to the performance of the pavement. Particle angularity, texture and shape are among the aggregate characteristics with significant effects on performance. These properties vary widely with the type and source of aggregates and production processes.

Within an asphalt mix, a good stone-on-stone aggregate structure within the asphalt lift serves as a skeleton, so to speak, which enhances asphalt pavement performance, boosting resistance to rutting and lowering internal strains that boost pavement fatigue life. The structure is made possible by extensive crusher processing, which creates multiple broken faces which abut each other within the asphalt lift.

Alkali-Silica Reactivity

Due to its high rigidity and compressive strengths, high-performance portland cement concrete is more forgiving than asphalt mixes when it comes to the configuration of aggregate particles. But not so when it comes to the kind of aggregates used, and alkali-silica reactivity (ASR) and related ills require careful screening of aggregate for PCC, at increased cost.

ASR is a chemical reaction that occurs between the reactive silica in certain aggregates used to make concrete, and the alkalis (sodium or potassium) present in the concrete mix. The process spawns a gel that absorbs water and swells, exerting pressure that can lead to premature deterioration of the concrete. ASR's chemical reaction exerts expansive pressure on concrete, initiating map and longitudinal cracking in bridge decks and pavements, and longitudinal cracking in bridge columns.

ASR doesn't destroy concrete by itself. Rather, reactivity-weakened concrete is compromised to the point that normal wear-and-tear becomes prematurely destructive.

The cause-and-effect pattern in concrete that ASR inflicts – in which the "disease" of ASR provides a gateway for other destructive ills that finish the host off – has caused it to be called the "AIDS" of concrete. The best way to avoid ASR in new concrete is to take precautions in the mix design, practitioners report. These include testing aggregates for reactivity and use of low-alkali cements, suitable pozzolans, and lithium-based admixtures.

ASR conventionally has been thought only to afflict western states. But Strategic Highway Research Program publication C-343 – Eliminating or Minimizing Alkali-Silica Reactivity – stated the "potential for deleterious ASR in highway concrete exists in every state in the United States."

Use of premium, nonreactive ("innocuous") aggregates can be specified, but these may not always be available locally. Aggregates can change in composition from one end of the pit or quarry to the other, making positive identification difficult. And established tests for reactivity may allow too much variability in the results. Suppression of ASR is possible through vigilance, and today admixtures such as lithium compounds are proven to fight ASR.

Lithium admixtures can calm reactive rock, wrote Marcus J. Millard, Georgia Institute of Technology, in his 2006 paper Effects of Lithium Nitrate Admixture on Early Age Concrete Behavior. "Lithium admixtures, including lithium nitrate ($LiNO_3$), have been demonstrated to mitigate ASR damage, and are of particular interest for use in concrete airfield pavement construction, where ASR damage has been recently linked to the use of certain de-icing chemicals," Millard said.

Through the 1990s, the emphasis has been on preventing ASR in new construction by addition of $LiNO_3$ to freshly-mixed concrete. But admixtures don't address the troublesome problem of ASR in existing pavements. This gap is being addressed by Renew concrete treatment, a product of FMC Lithium Division, Gastonia, N.C., a penetrating lithium-based compound that will moderate, if not halt, ASR's destructive mechanisms.

When reactivity is attenuated with surface-applied solutions, repairs become cost-effective and meaningful, and can be undertaken with confidence. The SHRP study indicated that lithium compounds were most effective in combating ASR.

There are three possible ways to deal with ASR after it develops, FMC reports:

- If sufficient triaxial compression can be applied, the expansion can be contained. This is not an option for most geometries, but may be possible for some columns that support large loads.
- Drying the concrete will work if it's possible, but in most

outdoor structures, getting the moisture level low enough (below 80 percent relative humidity) is impossible.
- Impregnation of the concrete with sufficient lithium ions will control the reaction. SHRP researchers demonstrated this with lithium hydroxide solutions, but they observed that penetration was minimal and the caustic nature of hydroxide solutions made the procedure problematic. Also, it was found that hydroxide solutions added alkalis to the concrete mix.

Instead, the Renew lithium nitrate solution can be sprayed on concrete surfaces, ponded on surfaces, or pressure-injected into concrete. Demonstrations suggest surface treatment quantities ranging from 3 to 9 gallons per 1,000 sq. ft., with 6 gallons per 1,000 sq. feet being the norm. If the solution is sprayed on, repeat applications over time should be considered, FMC reports.

ASR at the Nanoscale

FHWA's Advanced Infrastructure Research program has been conducting research on ASR, including research in Colloidal Chemistry of Alkali-Silicate Reaction (ASR) Gels.

This involves fundamental research into the chemical and physical processes that cause ASR gel damage. The ASR gel expansion mechanism appears to involve a phase transformation from amorphous gel to layered structure on the nanoscale, FHWA reports. The research includes the application of neutron scattering and positron annihilation spectroscopy to measure nano and sub-nanoscale changes in gel microstructure as a function of gel chemistry, temperature and relative humidity.

Other FHWA research has included:

- Fly Ash Reactivity Characterization. This FHWA-funded research is a fundamental look into the interactions between fly ash, and the portland cement gel nanostructure, that affect the strength and durability of concrete, including ASR reactivity. It includes the use of small angle neutron scattering to quantify the changes on a nanoscale as a function of time and fly ash composition. A unique vibrational spectroscopy also is being employed to nondestructively measure the reactivity of fly ashes.
- Aggregate ASR Potential Tests. ASR in concrete can be precluded by using nonreactive aggregates. This FHWA research involves fundamental research into the formation of ASR gels by reaction with different types of aggregates, using solid state nuclear magnetic resonance (NMR) to measure the formation of silicate chains on the nanoscale.

- Delayed Ettringite Formation Damage. Delayed ettringite is an internal sulfate attack on concrete. The FHWA research was exploring how delayed ettringite forms and causes damage in concrete, in transforming from an amorphous ettringite gel to nanoscale crystals. The research involves the application of synchrotron radiation to study the relationship between ettringite crystal formation and concrete expansion.

Lightweight Aggregates

Lightweight aggregates comprise a ceramic material produced by expanding and vitrifying select shales, clays and slates in a rotary kiln. This pyroprocessing produces an aggregate that is structurally strong, durable, environmentally inert and low in density, according to the Expanded Shale, Clay and Slate Institute. Such aggregates are ideal for use in applications where weight is an issue, for example, as aggregates in mixes for bridge decks.

Synthetic aggregates can be made from recycled materials. For example, in the SYNAG process of the Western Research Institute, coal combustion fly ash is cold-bonded chemically to produce a hardened product that can be crushed and sized for construction applications, with properties speci¬fied by ASTM and AASHTO.

Lightweight aggregates refer to a class of building materials that weigh less than 70 lb. per cubic foot, but more than 55 lb. per cubic foot (lightweight aggregates less than 55 lb. per cubic foot are used in insulation, agriculture or horticulture, but are too weak for use in robust applications). They generally exhibit a porous structure, with the weaker, lighter aggregates exhibiting high porosity, and the stronger displaying a finer, more evenly distributed porosity.

Aggregates produced by altering both physical and chemical properties of a parent material may be considered synthetic or artificial aggregates. Some are produced and processed specifically for use as aggregates; others are the byproduct of manufacturing and a final burning process, such as ground granulated blast furnace slag.

While there are naturally occurring lightweight aggregates -- such as pumice and other volcanics -- these tend to be too light and weak for construction use. Instead, engineers prefer "pyroprocessed" natural materials, that is, those that have been chemically and physically altered by the heat of a rotary kiln.

Pyroprocessed lightweight aggregates include those made from shale, clay and slate, which expand into lightweight aggregates when heated to temperatures in excess of 1000 deg C (1800 to 2100 deg F). This synthetic lightweight aggregate, according to ESCSI is a ceramic material produced by expanding and vitrifying select shales, clays, and slates in a rotary kiln, not unlike cement manufacture, but at a lower temperature.

"The process produces a high quality ceramic aggregate that is structurally strong, physically stable, durable, environmentally inert, light in weight, and highly insulative," ESCSI says. "It is a natural, non-toxic, absorptive aggregate that is dimensionally stable and will not degrade over time."

Clay is a very fine-grained, moisture-retentive, naturally occurring material composed principally of aluminum silicate compounds, derived from the decay of igneous micas and feldspars, such as found in granite. Sedimentary rock made from clay is called shale, and if it is metamorphosed it becomes slate. Thus pyroprocessing of all three materials – clay, shale and slate – results in essentially the same product, a lightweight aggregate that is ceramic in nature.

Aggregates and Unpaved Roads

Two-thirds of the road network system in the United States – and nearly 90 percent of the roads in the world – are unsurfaced or lightly surfaced low-volume roads. These unpaved roads may be surfaced with crushed stone, gravel or dirt – or even covered with a chip seal – but an aggregate/fines mix is a very popular combination for surfacing.

If unpaved roads must serve year-around traffic under all weather conditions, then aggregate surfacing is the best solution. The South Dakota Local Technology Assistance Program (LTAP) recommends a minimum of 3 inches of aggregate, which won't provide much structural strength, but provides the minimum amount of aggregate for blade maintenance purposes that will permit an operator to shape and work the aggregate without getting into the earth subgrade.

Dust from unpaved road aggregates can be controlled by periodic distribution of water, by establishment of a dust-suppressive, moisture-absorbing crust on a road surface, and by best management practices. Water is the traditional dust suppressant, as moisture increases the mass and cohesion of dust particles. Moisture helps fines adhere to each other and to aggregates, allowing for optimum compaction under traffic. However, no agency can afford to send water tankers on daily rounds on its unpaved roads. Instead, dust palliatives are an alternative to water. Spread by distributor truck, they suppress dust on a driving surface, keeping moisture in the road.

Chemical road treatments or palliatives work to keep dust in control. Generic examples of these chemical palliatives include anionic asphalt emulsions, latex emulsions, resin-water emulsions, and magnesium and calcium chloride. When considering chemical palliatives for dust suppression, the agency should ascertain whether the chemical is biodegradable or water-soluble, and what effect its application could have on the surrounding environment, including water bodies and wildlife.

Liquid magnesium chloride and calcium chloride are very common dust palliatives which absorb humidity from the ambient air, suppressing dust by keeping it relatively damp. $MgCl$ and $CaCl$ absorb water vapor from the air and moisture extant in the road structure. At 77 degrees F and 75 percent humidity – common conditions during summer in the Midwest and South – $CaCl$ absorbs more than twice its weight in water. In addition, such solutions attract more moisture to the road than they give up in evaporation. Thus a treated road surface can retain moisture even during the heat of summer.

'Smart' Aggregates

Research continues into aggregates that provide no compressive strengths to concrete at all; instead they are manufactured products which permit monitoring of movement or stresses within concrete, and may incorporate nanotechnology in their functions.

For example, piezoceramic-based devices – dubbed "smart" aggregates – someday may monitor dynamic seismic response and perform structural health monitoring for large-scale concrete structures.

In their paper, Smart Aggregates: Multi-Functional Sensors for Concrete Structures, Gangbing Song, Haichang Gu and Yi-Lung Mo, University of Texas-Houston, describe pioneering research work in piezoceramic-based smart aggregates and their innovative applications in concrete civil structures.

Piezoelectricity describes an electric charge that is developed within a crystalline or ceramic material when that material is stressed, moved or disturbed. Their proposed smart aggregate is formed by embedding a waterproof piezoelectric patch with lead wires into a small concrete block.

These proposed smart aggregates are multi-functional and can perform three major tasks: early-age concrete strength monitoring, impact detection and structural health monitoring. The smart aggregates would be embedded into the desired location before the casting of the concrete structure.

The concrete strength development is monitored by observing the high frequency harmonic wave response of the smart aggregate. Impact on the concrete structure is detected by observing the open-circuit voltage of the piezoceramic patch in the smart aggregate.

But smart aggregate sensors need the ability to communicate via wireless connections to various forms of readout systems. Many applications for sensors are in remote and embedded locations where wired or optical connections are not practical or economical, reports Johns Hopkins University. Sensors in these applications need to be small, rugged and long-lived. Support platforms need to be able to adapt to a large variety of sensors including pressure, temperature, conductivity and analytical.

The Johns Hopkins University Applied Physics Laboratory has developed and patented the Wireless Embedded Sensor Platform (WESP). The initial application for this technology was a program which embedded the sensor, transducer and communication system in concrete to measure the corrosion of rebars.

The WESP is small (about the size of a quarter), rugged (made of high compression strength ceramics) and versatile (capable of being integrated with a wide variety of sensor elements), long lasting (no battery), and wireless. A remote transmitter powers the WESP up from a sleep mode, the sensor readings are converted in the WESP and transmitted to a receiver, and once the measurement is made the unit goes back to sleep until the next request is made. ❖