HIGHWAY MATERIALS AS AGGREGATE-BINDER COMPOSITES

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For many years engineers and scientists in geology, soil mechanics, and paving technology have contributed their efforts to improve the quality and economy of materials used in highway construction. Yet there has been a tendency to neglect the fact that the materials these specialists study possess a common denominator: All are aggregate-matrix composites. This paper provides a tentative classification of the materials involved in these 3 fields to support the claim that they can be organized by the systems approach. Unfilled binders, such as clay and asphalt cement, occur at one extreme of the composite spectrum; unbound fillers, such as clean sand and rock base, occur at the other. Examples are cited from particulate, viscoelastic, and graphic models that have interdisciplinary acceptance in displaying the rheological behavior of highway materials. In education, it is not enough that the student be taught how much different one conventional paving material is from another. More use should be made of those phenomenological tools and physical testing procedures that will enable the student to use the diverse combinations of fillers and binders being created to meet pressing economic and ecological needs.

●BEFORE an engineer can understand and intelligently apply the principles of the design of highway pavement structures, he or she must be fully aware of the mechanical properties of the materials with which pavement systems are constructed. It is common knowledge that these systems consist of 1 or more layers of materials called courses supported on a foundation material called the subgrade. These materials belong to a category called composites; composite materials are classified as particle-reinforced, fiber-reinforced, and sandwich-reinforced. In pavement technology, the particulate system can be called an aggregate-binder composite.

In the past, highway aggregates have usually consisted of natural gravel, crushed rock, slag, or 1 of a variety of recycled products used on an experimental basis. The binder has consisted of a material such as portland cement paste, tar, cohesive soil, lime paste, or asphalt cement and may have contained a property-modifying admixture. It seems reasonable to expect that those involved with research, design, or construction of pavement systems possess adequate training in geology, soils, and concrete technology. Traditionally, there has been a tendency to compartmentalize the efforts of the specialists in these fields. Standard American textbooks on highway engineering have tended to emphasize the differences, for example, between portland cement and asphalt concretes rather than present a comprehensive approach to the understanding of both. The absence of such an approach to the mechanics of roadway materials reflects the past state of an industry content with such unqualified terms as "blacktop" and "cement pavement" in its technical vocabulary. The present annual investment of billions of dollars for research, development, and manufacture of highway pavements justifies a more rational attitude toward this important subject. A unified approach to pavement systems would facilitate education and design and, ultimately, make a more economical use of various highway materials.

This paper covers viscoelastic behavior of pavement joint fillers, expansion device materials, and elastomeric bridge bearings.

Publication of this paper sponsored by Committee on General Asphalt Problems.

AGGREGATE-BINDER SYSTEMS

How well do geology, soil mechanics, and concrete technology fit into a unified classification system? Table 1 gives a classification of the materials in these systems. The engineering geology column should apply only to sedimentary rocks and geologically unconsolidated sediments, but because these sediments sometimes contain igneous and metamorphic rock particles, they also are included. The soil mechanics column indicates that clean sand and remolded, fully saturated clays form the extremities of behavioral response in soil mechanics; usually, a little less than one-third of these by volume of cohesive soil are required to give a mixed soil rheological characteristics. Only the more commonly used concrete composite materials are included in the fourth column.

The highway cross section shown in Figure 1 is an example of a layered system that contains a variety of aggregates and binders including, remarkably, a strain-relieving interlayer that contains a binder almost as rigid as its filler. The shortage of economical sources of natural aggregates in some parts of the world has led to an exploration for suitable synthetics, and the technical literature is replete with a bewildering variety of binder admixtures, modifiers, patented cements, joint compounds, and bridge bearing materials. The conventional "they're either rigid or flexible" approach to highway materials has been abandoned because in layered-systems technology the number of mathematical combinations of compatible aggregates and binders spans the rigidity spectrum (1).

A study of Highway Research in Progress reveals the extent to which research in geology, soils, and paving materials is now going on (2, 3). Bituminous binders are being modified by rubber latex, asbestos fillers, chopped fiberglass, colored synthetic resins, tar-asphalt blends, powdered glass, and synthetic textiles. Portland cement is being used with polystyrene, silicones, polymer latex emulsions, synthetic polyester systems, alumina filaments, and in self-stressing, expansive applications. Cement-stabilized chalk, spent oil shale, gypsum, formed plastics, synthetic and organic polymers, bamboo fibers, and lignosol are some of the materials being used here and abroad to remedy structural deficiencies in base course and shoulder materials. Dramatic, ecology-promoted innovations are taking place in aggregate technology. Among the new materials being researched are ceramics, porous particles, cement-stabilized soil nodules, crushed moraine, sideritic concretions, anthracite mine waste, steel fibers, calcined bauxite, recycled plastic chips, cement clinker, building rubble, boiler slag, marine deposits, burned garbage, crushed glass, cast iron, vulcanized rubber particles, and reclaimed pavement surfacings. It seems reasonable to expect that as the use of more of these materials becomes economically feasible, the classical distinctions between portland cement and asphalt-bound materials will become increasingly blurred.

PHENOMENOLOGICAL MODELS OF AGGREGATE-BINDER MATERIALS

Particulate Models

During the years when the art of soil mechanics was becoming a science, particulate models were used as a research and teaching aid by such outstanding engineers as Casagrande, Taylor, and Terzaghi. Figure 2a shows a model of the honeycomb structure found in fine silts and clays and represents, therefore, the binder fraction of soil or material passing the No. 200 sieve (4). Figure 2b is taken from Gilboy (5) and clearly indicates that the flexural response of the mica platelets in a sand-mica soil causes excessive compressibility in this material. A model referred to by Holmes (6) is shown in Figure 2c as an example from physical geology. Sandstones can be thought of as natural concretes in which the aggregate frequently consists of fragments of disintegrated older rocks. This model shows graded graywacke; such layers often extend over large areas and are surprisingly uniform in thickness.

Figures 2d, e, and f are examples of particulate models on a larger microscopic scale than the preceding 3. To emphasize to students the importance of a rough aggregate surface texture to the stability of an asphalt concrete mixture, Monismith (7)

Table 1. Aggregate-binder systems used in highway engineering.

Category	Engineering Geology	Soil Mechanics	Concrete Technology
Unbound aggregate subsystem	Marine shells, mica flakes, silts, quartz sands, gravels, boulders, talus, volcanic ash, and fragments of detritus	Clean sand, river-run gravel, boulders, rubble, riprap, and other cohesionless construction materials	Clean granular base course materials, unbound macadam, crushed rock, and selected imported granular fills
Unfilled binder subsystem	Silica, carbonate, dolomite, clay, gypsum, haematite, limonite, clay shales, and other cementing minerals	Remolded clay, fine silts, water binders, lime, chemical additives, and other soil stabilizers	Portland cement paste, road tar asphalt cement, cutbacks, emulsions, elastomeric bearings, and joint fillers
Aggregate-binder system	Loess, alluvium, moraine, muddy grits, limestone, sandstone, siltstone, breccias, conglomerates, porphyrys, and grouts	Glacial till, manmade compacted mixed-soil roadway embankments, soil cement, and asphalt mixtures	Portland cement and asphalt concretes, grout, sand asphalt, bituminous macadam, filled elastomers, and bridge bearings

Figure 1. Cross section of a complex layered system of composite highway materials.

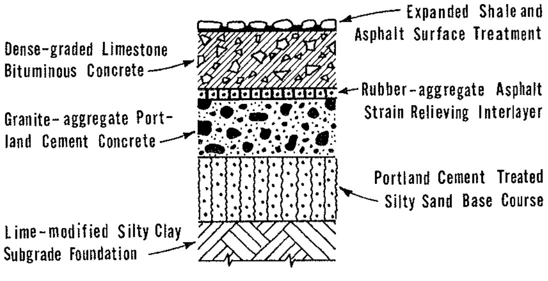


Figure 2. Particulate models from geology, soil, concrete, and composite materials technology.

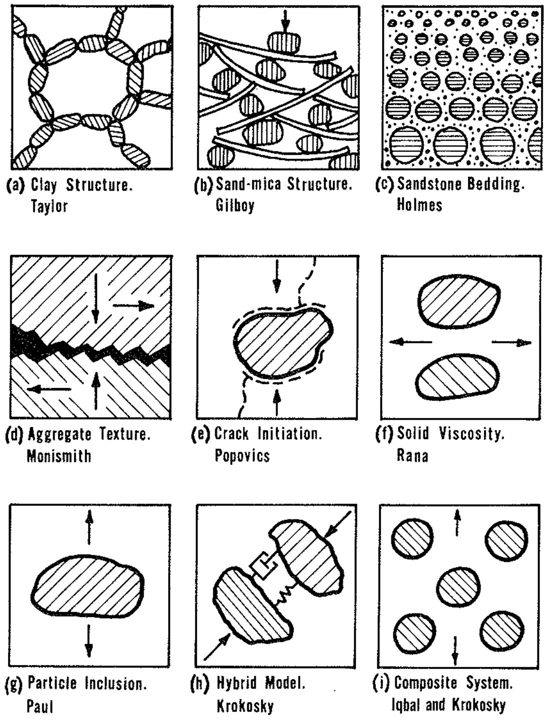
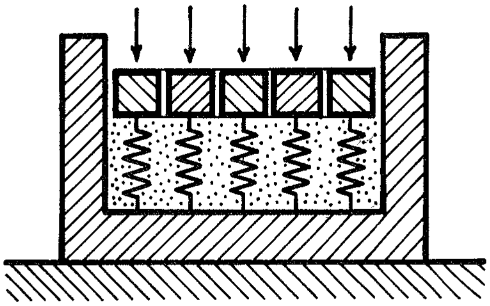

(a) Clay Structure. Taylor
(b) Sand-mica Structure. Gilboy
(c) Sandstone Bedding. Holmes
(d) Aggregate Texture. Monismith
(e) Crack Initiation. Popovics
(f) Solid Viscosity. Rana
(g) Particle Inclusion. Paul
(h) Hybrid Model. Krokosky
(i) Composite System. Iqbal and Krokosky

Figure 3. Clay subgrade, early Terzaghi rheological model.



used the model of Figure 2d. The exaggeration of the roughness at the rock interfaces with the asphalt film is intentional. In a paper on the fracture mechanism of portland cement concrete, Popovics (8) used the model of Figure 2e to illustrate crack initiation and propagation in the mortar. At about 70 to 90 percent of the ultimate load, cracks (shown as broken lines in the model) through the mortar begin to increase appreciably; because of bridging between nearby bond cracks, a continuous network of cracks is formed. Figure 2f was used by Rana (9) in a paper on the viscosity of rocks. Rana stated that design criteria in rock technology, until quite recently, were based on the classical theory of elasticity, and he found that there were very few experimental data on solid viscosity of geological materials.

The model of Figure 2g was used by Paul (10) in his general solution to the problem of an elastic particle in an elastic matrix. The modulus of this system is a function of the modular ratio and the volume ratio of particles to matrix. Paul's analogy of a particle within a cubic matrix is restricted in usefulness to composites with a low volume ratio and no particle interlock. These limitations are critical for highway materials where volume ratios are relatively high and aggregate interlock may be very significant. Counto (11) used a cylindrical particle within a cylindrical matrix as his model to determine the effect of the modulus of the aggregate on the elastic modulus, creep, and creep recovery of portland cement concrete. To compare his model response with actual test results, he prepared concrete specimens that contained steel, flint, cast iron, and polythene coarse aggregates in order that the particles possess a wide range of elastic moduli and low water absorption.

Figure 2h was used by Krokosky (12) in illustrating the effect of temperature on the mechanical properties of an asphalt concrete. The asphalt film separating the particles of aggregate is depicted as a Kelvin material; this hybrid model was suggested by Krokosky as a rough approximation of the response of an asphalt concrete tested at temperatures between glass transition and about 100 F. Although conventional portland cement and asphalt concretes are sometimes described as 2-phase composites, the mixing operation usually creates an air-void phase even when air entrainment is not intentional. Figure 2i is from a paper by Iqbal and Krokosky (13) on their analysis of an idealized elastic composite system using the finite-element method. Each circle in the model can be used to represent either a cylindrical particle or an air void. They selected a particle to binder modular ratio of 100 and treated the voids as particles possessing a very small but finite dummy modulus. Hackett (14) used a model similar to Figure 2i and conducted a stress analysis for the case of an elastic particle in a viscoelastic binder, a solution that could fit those construction materials with marked rheological properties.

Viscoelastic Models

The use of viscoelastic or rheological models in analyzing the physical properties of aggregate-binder materials in geology, soil mechanics, and concrete pavement technology is well established. In 1927, Terzaghi (15) presented a paper on the importance of sound foundation engineering in the construction of portland cement concrete roads. He used the rheological model in Figure 3 to approximate the response to load of a layer of fully saturated clay. A rheological model can be used for highway composites in 3 different ways. It can model an unfilled binder such as a paving asphalt or a bridge-bearing elastomer; an unbound filler such as crushed rock or clean sand; and a complete system such as portland cement concrete, a mixed soil, or a consolidated sedimentary rock. To conserve space, alphabetical symbols have been used for the models and their elements in Figures 4 and 5. The conventional spring and dashpot element symbols are shown at the left of Figure 4a (16).

In Figure 4b, block M represents a spring and dashpot series configuration with each element equally stressed; block K represents them in parallel with each equally strained; the former model has been used by Emery (17) in the field of rock mechanics. Dennis (18) has suggested that the firmo-viscous deformation of some unconsolidated geological materials under stress can be approximated by a Kelvin model. A Maxwell and a Kelvin model connected in series are indicated in Figure 4c as block B; George (19) used this

Figure 4. Some commonly used viscoelastic models and symbols.

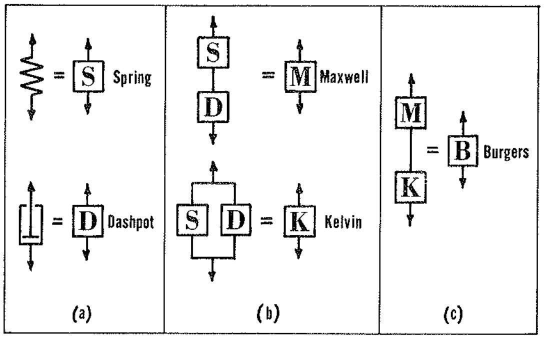


Figure 5. Additional viscoelastic models using elements from Figure 4.

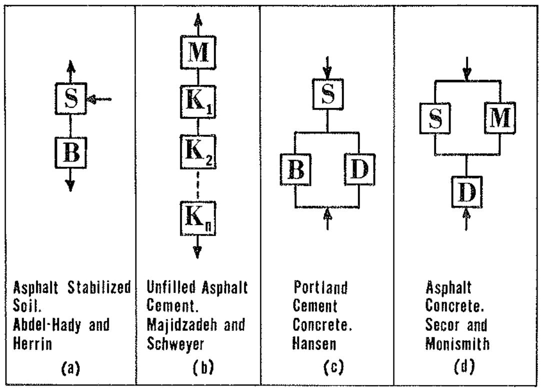


Figure 6. Unspecified load on a hypothetical material.

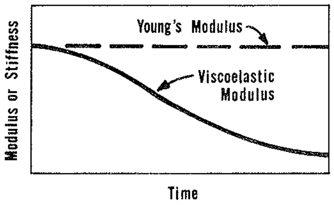
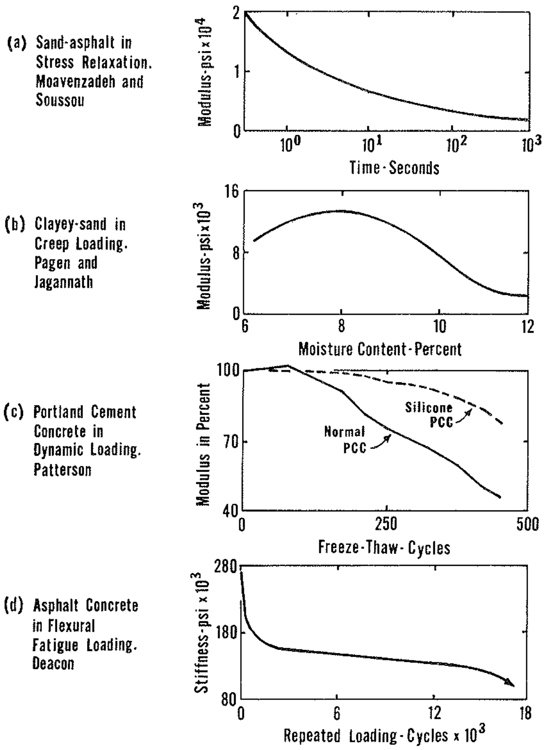


Figure 7. Graphic models, modulus dependency functions.



mechanical model in his analysis of shrinkage stresses in a sand-clay base course stabilized with portland cement. Using the model of Figure 5a, Abdel-Hady and Herrin (20) applied the theory of rate process and fairly accurately approximated the nonlinear viscoelastic response of an asphalt-stabilized soil. In their model, the free spring is modified by use of a stop (horizontal arrow) to represent the initial plastic deformation of this material under creep loading. Majidzadeh and Schweyer (21) subjected aged and unaged specimens of asphalt cement to creep tests at 32 F to better understand aging phenomena. The model they used to fit their data is shown in Figure 5b and consists of a Maxwell part in series with a selected number of multiple-parameter Kelvin parts that are, in turn, in series with each other. The Hansen model (22) for creep in portland cement concrete is shown in Figure 5c. The free spring represents the relatively elastic response of the aggregate phase; the dashpot represents the water and voids; and the Burgers part incorporates the effects of the gel, unhydrated cement, and crystalline products of hydration. The model of Figure 5d consists of a spring and a Maxwell part parallel to each other and collectively in series with a free dashpot; Secor and Monismith (23) used this model to predict the response to constant rate of compression loading of a particular asphalt concrete mixture.

The rheological models presented in Figures 3, 4, and 5 are deterministic because they represent ideal materials; that is, they predict response to load with a probability of unity. Gabrielson (24) used the concept of random spring and dashpot components in stochastic Maxwell and Kelvin models. This stochastic approach to viscoelastic behavior is particularly relevant to highway engineering materials because scatter of test data for particulate composites is more pronounced than for more homogeneous materials.

Graphic Models

In the context of this paper, a graphic model is defined as a plot of a theoretically or empirically derived modulus dependency function. Such a function has modulus or stiffness of a material as the dependent variable and time, temperature, or other significant factor as the independent variable or argument (16). The time-dependent modulus is a common example of a modulus dependency function. Figure 6 shows a schematic time-dependent modulus for an unspecified mode of loading (25); it incorporates both the viscous and elastic responses of a rheological material and could logically be called a viscoelastic modulus. Could the viscous parameter of this hypothetical material be made to approach infinity, its viscoelastic modulus would degenerate to Young's modulus as indicated on the figure; and at very short times, of course, all rheological materials tend to perform elastically.

A stress relaxation modulus is a time-dependent modular function for a material loaded in a specified environment under a constant-strain model. Figure 7a is the stress relaxation modulus in unconfined compression for a sand-asphalt mixture tested by Moavenzadeh and Soussou (26) at 35 C. Values of the argument of a modulus dependency function can be continuous or discrete; the plot of Figure 7a is an example of the continuous case and that of Figure 7b is discrete. Figure 7b is from a Pagen and Jagannath study (27) in which linear viscoelastic theory was used to provide a more rational method of determining the optimum moisture content in highway subgrade compaction operations. The ordinate represents the elastic part of the unconfined compressive creep modulus at 30 sec and the abscissa represents the molding water content of specimens compacted at 25 blows. The curve was fitted to data points plotted at discrete values of water content for specimens of clayey sand, a classical aggregate-binder material. In portland cement concrete technology, the dynamic modulus of elasticity has been used to measure the effectiveness of a silicone admixture in improving the resistance of a concrete bridge deck to repeated cycles of freeze-thaw. In Figure 7c, from Patterson (28), the upper plot contains dynamic modular data for silicone deck concrete and the lower one for normal concrete. This modulus is freeze-thaw-cycle dependent.

The moduli of bituminous materials and bearing elastomers are highly susceptible to temperature change; those of soils and other geological deposits may be sensitive to moisture content or confining pressure, but fatigue-damage susceptibility is a property of all pavement and subgrade materials. Because major highways are subjected to millions of repetitions of a variety of axle loads during their service lives, the effect of cumulative fatigue damage on the moduli of highway materials is of interest to researchers and students in all areas of pavement materials technology. Figure 7d is from a thesis by Deacon (29) in which he provided dynamic deflection data from stress-controlled fatigue tests on an asphalt concrete mixture. He plotted the stiffness modulus of the mixture as a function of the number of load applications under a 113.5-psi flexural stress at 75 F.

This author has found that the behavioral response of a wide variety of highway materials can rapidly be demonstrated by plotting the appropriate modulus dependency functions.

CONCLUSIONS

An interdisciplinary approach to understanding the response of paving materials must begin in our educational system. I am not suggesting that courses in engineering geology, soil mechanics, and highway materials be replaced by a catch-all course in composite materials technology or aggregate-binder systems but that the first course in highway engineering or pavement materials be designed to devote a few lectures to a holistic approach to the behavior of stone-matrix materials. Table 1 presents a tentative classification of geological, soil mechanics, and concrete materials in an attempt to support the belief that they can be conceived in terms of aggregate-binder systems.

It is important that every available teaching aid be used to impress on students that predicting the behavior of complex rheological composites demands exacting interpretations of their loading histories. I recommend using 3 time-tested phenomenological models to achieve this end: particulate models, viscoelastic models, and graphic models. Particulate models develop a feeling for material response at the largest macroscopic scale; viscoelastic models give physical analogy to linear theory; and graphic models (modulus dependency functions) provide a ready tool for displaying empirical data. Some of the models presented in this paper are taken from the writings of eminent engineering educators and others from technical papers expounding important advances in the field of paving technology. Because these phenomenological aids were used to communicate new theoretical and empirical concepts to experienced researchers in the field, it seems reasonable to conclude that their use is even more vital in presenting a unified system of highway materials to students headed for careers in highway engineering.

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