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# Engineering Properties of Recycled Organic Aggregate for Controlled Low-Strength Materials

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## ABSTRACT

Fine aggregate is one of the main constituents of most controlled low-strength materials (CLSM). Traditionally, natural sand is used as the source of fine aggregate. Recycled materials such as quarry fines and foundry sands have been used as replacements for sand. These materials are similar in composition because each is derived from inorganic sources. Organic aggregate can impart special physical and mechanical properties when used to produce CLSM. This paper reviews the potential sources and properties of recycled organic aggregate, including crumb rubber, wood chips and sawdust, ground asphalt shingles, and shredded plastics. The engineering properties of each potential source can be used to guide the appropriate aggregate selection and mixture proportioning. CLSM produced with recycled organic aggregate will be lightweight, ductile, and insulating when compared to conventional CLSM.

## INTRODUCTION

Conventional CLSM mixtures consist of portland cement paste, coal fly ash and/or other pozzolans, and fine aggregate that is sometimes blended with coarse aggregate. Aggregates are usually the major constituent of a CLSM mixture. Fine aggregate sources for CLSM include concrete sand per ASTM C33/C33M, natural sands containing up to 20% silt, and washed screenings or manufactured sands. Pea gravel or pea stone with sand is commonly utilized when coarse aggregate is required. Non-standard aggregate sources are acceptable and often encouraged when available. Selection of aggregate should be based on cost, application, and required mixture properties. The selection process is important because the type, grading, shape and texture of aggregates influence the physical and mechanical properties of the fresh and hardened CLSM mixture.

The effects of replacing natural aggregate with inorganic waste products on CLSM mixture properties have been well published in the technical literature. Examples of inorganic waste products include crusher fines, recycled crushed concrete [e.g. Achtemichuk et al. 2009], discarded foundry sands [e.g. Tikalsky et al. 1998, 2000; Deng and Tikalsky 2008; Siddique and Noumowe 2008] and waste glass [e.g. Wang and Chen 2008; Her-Yung 2009]. While the total chemical composition varies among these waste products, the bulk of their composition contains the same inorganic compounds found in natural aggregate such as alumina, silica, and calcium and sodium carbonates.

In these cases, CLSM mixtures produce a solid inorganic composite material. Replacing inorganic aggregate with organic aggregate produces a solid inorganic-organic composite material that can have significantly different engineering properties. CLSM with organic aggregate can reduce density, stiffness and strength, which can be desirable in applications where self weight must be limited and future excavation is required; increase ductility, which allows for more plastic deformation and can reduce cracking; and increase insulation properties for applications where buried pipe or power lines require electrical or thermal protection. This paper reviews potential sources of recycled organic aggregate for CLSM that include roofing shingle scrap, plastic waste, scrap tires, and wood waste.

## BACKGROUND

Inorganic compounds tend to exhibit brittle fracture due to the nature of the covalent and ionic bonds. During production, the formation of internal cracks and flaws give rise to stress concentrations that lower the material strength and fracture toughness. Organic solids often have distinguishable properties from inorganic solids. All organic solids are composed of long molecular chains of covalent bonded hydrocarbons that are linked with secondary bonds and, in some cases, cross-linked with covalent bonds. Mechanical properties are a function of the molecular chain length and the extent of cross-linking. Stiffness and strength of organic solids are often lower than inorganic solids but exhibit more ductile fracture.

The molecular composition of organic solids also influences its physical properties. Organic solids are lighter than most inorganic solids because of the lower molecular weight of hydrocarbons. Organic solids can also have higher electrical and thermal insulating capacities.

Changes in composite behavior are a function of the organic aggregate behavior. There are four engineering classifications of organic solids: thermoplastics, thermosets, elastomers, and natural materials from plant matter. Thermoplastics are not cross-linked which causes mechanical response to be temperature dependent. Asphalt is a natural thermoplastic. Polymers such as polyethylene (PE), polystyrene (PS), and polyvinylchloride (PVC) are manufactured thermoplastics. Thermosets can have extensive cross-linking that prevents softening when heated. Polyester fiber is a common example of a thermoset. Elastomers are referred to as rubbers and have more limited cross-linking. Polyisoprene is a natural rubber and polybutadiene is a synthetic rubber. Natural materials like wood are composed of loose bonds between cellulose and lignin, which are two of the most abundant organic polymers.

## SOURCES OF RECYCLED ORGANIC AGGREGATE

Studies on organic aggregate replacement in CLSM have been limited to crumb rubber manufactured from scrap tires [e.g. Pierce and Blackwell 2003]. Yet there are other organic sources of recycled materials that warrant consideration because those materials are acceptable as aggregate in portland cement composites or asphalt cement composites.

It should be noted that most CLSM mixtures include coal fly ash, which contains variable amounts of residual carbon. This unburned carbon can be granular but is considered incidental to the aggregate content. Coal bottom ash, which is accepted as aggregate for CLSM, is an inorganic solid composed of alumina, silica, and iron but with some carbon content. Neither source is considered herein as an organic aggregate because the carbon content is incidental and, in some cases, can be quite low.

Organic ashes have been used in CLSM, such as wood ash [e.g. Siddique 2009] and rice husk ash [e.g. Nataraja and Nalanda 2008], but these materials exhibit pozzolanic properties and are not considered as aggregate. Asphalt dust has also been studied as a fine admixture in CLSM [Katz and Kovler 2003].

### Asphalt Shingles

Roofing shingles are composed of a felt backing (5-15% of total weight) that is saturated and coated with asphalt cement (25-30%) and surface coated with mineral granules (60-70%). The backing consists of either organic felt produced from cellulose fibers or glass felt produced from fiberglass. Roofing shingle scrap, like recycled asphalt pavement (RAP), is different from most recycled construction materials in that it is an inorganic-organic composite. Roofing shingle scrap is typically shredded to 38 mm (1.5 in.) and milled to a nominal size of 9.5 mm (0.4 in.) or finer. A photograph of shredded shingles is shown in Fig. 1, which illustrates separation of fibers from the asphalt-mineral matrix.

Roofing shingle scrap and RAP are both acceptable materials in asphalt pavement mixtures but are generally not used in portland cement-based materials. The organic content of shingles ranges from 25-40% of total weight depending on the asphalt content and whether or not cellulose fibers are present. However, the organic content in RAP is much lower because the asphalt content is limited to a range of 3-7%. Thus RAP is not considered herein as an organic aggregate source.

### Scrap Plastic

Recycling plastics is complicated because there are substantially different polymer types that enter the construction and municipal waste streams. Most are synthetic thermoplastics. The plastics industry created a numbered sorting scheme that designates plastics as polyethylene terephthalate (1), high density polyethylene (2), polyvinyl chloride (3), low density polyethylene (4), polypropylene (5), polystyrene (6) and other (7). Mechanical processing of scrap plastics is accomplished by shredding or grinding. Granulated plastics can be pelletized through extrusion and agglomeration or densification.

Fig. 1. Roofing Shingle Scrap after Initial Shredding.

### Scrap Tire Rubber

Scrap tires can be processed and reduced from large to fine particle sizes in the following order: whole tires, slit tires, shredded or chipped tires, ground rubber, and crumb rubber. The principal chemical composition of tires is a blend of natural and synthetic rubber. Carbon black and sulfur are also present along with belting materials that include steel fibers, fiberglass, and in some cases, nylon or polyester. Ground and crumb rubber is produced such that the steel and fabric belting are separated out from the rubber.

Ground rubber yields a coarse aggregate gradation. Particles can range in size from as coarse as 19 mm (0.75 in.) to as fine as 0.15 mm (No. 100 sieve) depending on the equipment and desired application. Crumb rubber is a fine aggregate with particles ranging in size from 4.75 mm (No. 4 sieve) to less than 0.075 mm (No. 200 sieve) depending on the process. A sample of crumb rubber is shown in Fig. 2a. Three methods are available to convert scrap tires to crumb rubber of different shapes and sizes [Heitzman 1992]. The granulator process shears apart the rubber to create granulated crumb rubber with particle sizes ranging from 9.5 mm (0.38 in.) to 0.5 mm (No. 40 sieve). The crackermill process creates ground crumb rubber, which consists of irregular shapes of torn particles with large surface areas. Particles range in size from approximately 5 mm to 0.5 mm (No. 4 to No. 40 sieve). The micro-mill process produces a fine ground crumb rubber with particle sizes ranging from 0.5 mm (No. 40 sieve) to as small as 0.075 mm (No. 200 sieve).

### Wood Waste

Different kinds of wood and wood waste are produced in the lumber industry. For the purposes of this paper, discussion on wood waste is limited to wood chips or shavings and sawdust. Wood chips are generally elongated wood particles produced from milling operations and can range in size from 6 mm (0.25 in.) to tens of millimeters (several inches) in length. Typically, chips are longer about one axis than the other and are thin compared to its length. Sawdust is produced from sawing lumber and can range from dust size particles to sand size particles, where the particle dimensions are more consistent in all three directions. A sample of sawdust from a lumber mill is shown in Fig. 2b. Waste from turning wood on a lathe can be as large as tens of millimeters (several inches) in length to as small as sawdust. These particles tend to be thin and curled as a result of the lathe action.

**Fig. 2. Fine Aggregate Gradations of (a) Crumb Rubber and (b) Sawdust.**

## PROPERTIES OF RECYCLED ORGANIC AGGREGATE

The physico-mechanical properties of recycled organic aggregates influence fresh and hardened CLSM properties. These properties must be accounted for when selecting the aggregate source and designing the mixture proportions. Ideally, the aggregate source is selected because it most appropriately meets the engineering requirements of a particular CLSM application.

### Specific Gravity

The bulk specific gravity, $G_{sb}$, of each recycled organic aggregate is less than that of inorganic aggregates. $G_{sb}$ for polymers generally ranges between 1 and 2 depending on the particular polymer. There are a few thermoplastics (e.g. low and high density polyethylene) and thermosets (e.g. low density epoxy) that have $G_{sb}$ less than 1.00. The nominal specific gravity of liquid asphalt is 1.00, but $G_{sb}$ for roofing shingles is higher (1.29 - 1.37) because of the felt backing and mineral filler. Ground and crumb rubber has $G_{sb}$ around 1.15 based on its blend of natural and synthetic elastomers.

The specific gravity of wood is less than 1.00, with a few exceptions, and some wood species like balsa ($G_{sb}$ = 0.17) are especially light. Wood is lighter than most polymers because of its unique pore structure, which can be observed in the SEM of a sawdust particle shown in Fig. 3. The tubular structure of the cellulose fibrils increases the void volume and reduces the bulk specific gravity of wood.

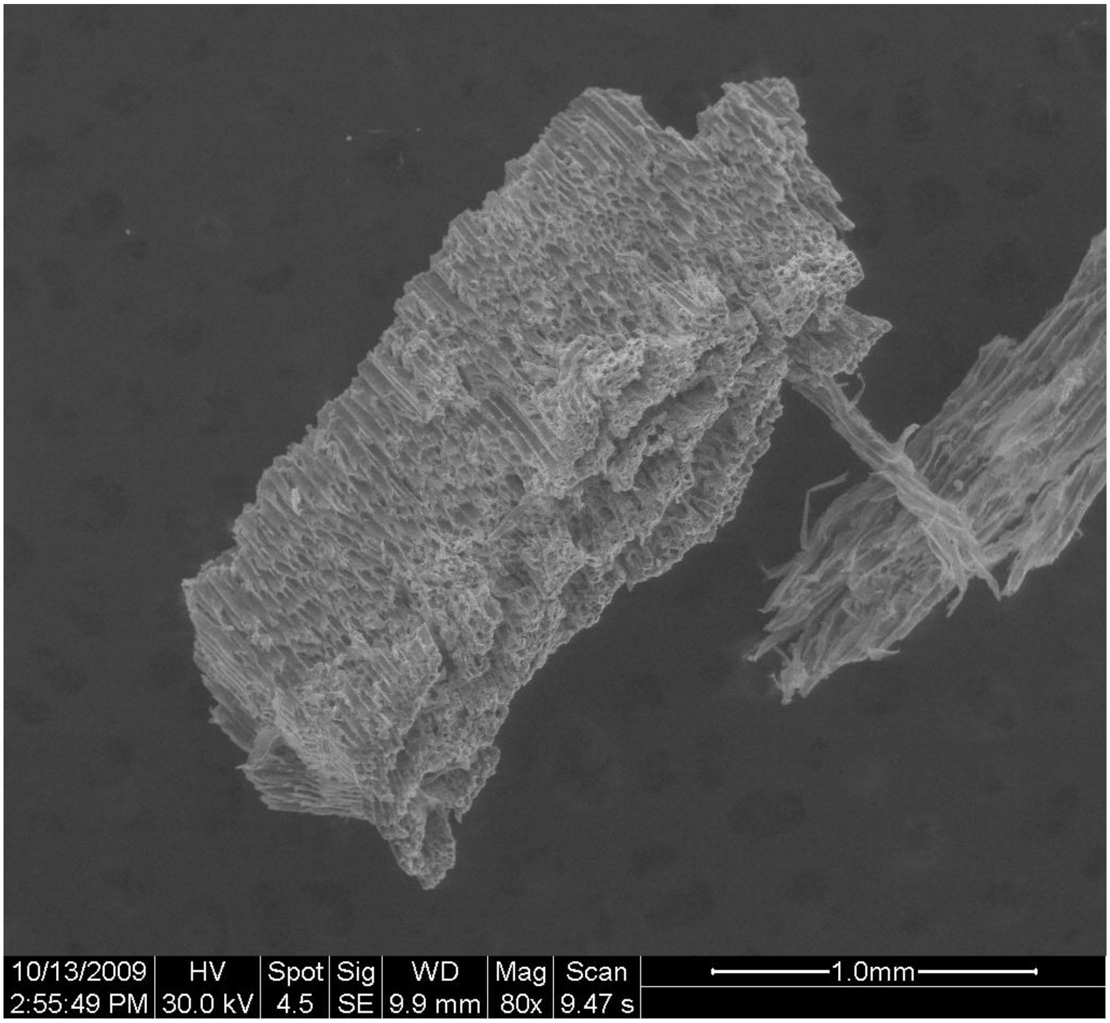

**Fig. 3. SEM of Southern Yellow Pine Sawdust Particle.**

The reduction in mass density of CLSM depends on the bulk specific gravity and volumetric fraction of recycled organic aggregate. For example, the mass density of CLSM with crumb rubber is 1.2 to 1.6 g/cm$^3$ (73 to 98 lb/ft$^3$) as compared to 1.8 to 2.3 g/cm$^3$ (115 to 145 lb/ft$^3$) for CLSM with standard sand [Pierce and Blackwell 2003]. The mass density of CLSM can be reduced further using an aggregate with $G_{sb}$ lower than that of crumb rubber.

### Absorption

The absorption of recycled organic aggregates can be less than, equal to, or greater than that of inorganic aggregates. The absorption characteristics of each recycled organic aggregate affect the required water content of the CLSM mixture and its volumetric stability while in service. Absorption is a function of the permeable pore volume, which can range from negligible to considerable depending on the polymer. Most thermoplastics have an absorption less than 1% of total weight. Absorption in some thermoplastics like polyethylene (as low as 0.01%) is insignificant and therefore does not need to be considered in mixture proportioning of CLSM. Other thermoplastics like nylon (as high as 9%) can be quite absorbent. Scrap tire rubber has an absorption between 2 and 4%, while roofing shingle scrap has an absorption as high as 10% for shingles with organic felt backing.

Wood absorption is even higher because of its pore structure. In wood, water is either adsorbed on the cell walls or absorbed in the cavities of the cellulose fibrils (see Fig. 3). The maximum adsorbed water content is called the fiber saturation point (FSP), which ranges from 21 to 32% for most wood species. Total water contents can be even higher if water is absorbed in the fibrils, but this free water does not change total volume. However, lumber is produced at water contents less than FSP, such that changes in water content cause shrinking or swelling of the cell walls. If not controlled, water in wood waste aggregate can be consumed through cement hydration or evaporation, leading to internal shrinkage of CLSM. Alternatively, water can be adsorbed on the wood waste aggregate from the paste, leading to internal swelling of CLSM. Volumetric stability of CLSM can be improved through the application of chemical sealants to the wood waste aggregate to mitigate water exchange.

### Shape and Texture

The shape and texture of recycled organic aggregate particles can be more irregular than inorganic aggregate particles. These physical characteristics affect fresh and hardened CLSM properties, such as flowability, bond strength, and composite stiffness. Shape and texture are a function of the mechanical processes used to reduce particle sizes. Fig. 4a illustrates a shredded roofing shingle, where the asphalt-mineral matrix is degraded into a rough, bulk particle that is mixed with individual strands of separated fibers. The fibers remain partially coated with asphalt cement, which roughens the fiber surface texture. Fig. 4b shows a crumb rubber particle after grinding. Cleavage on parts of the bulk particle surface can be observed, creating a smoother texture. Sawdust appears to be more elongated with a fibrous texture, as shown in the prior Fig. 3.

## SUMMARY AND CONCLUSIONS

Organic solids have engineering properties that are different from inorganic solids and that can be beneficial for controlled low-strength material (CLSM) applications. Yet research on recycled organic aggregate in CLSM has been quite limited. This paper summarizes the engineering properties of four recycled materials: roofing shingle scrap, plastic waste, scrap tire rubber, and wood waste. Through careful selection of the aggregate source, an inorganic-organic CLSM can be designed to produce a lightweight, ductile, and excavatable construction material with special properties such as electric or thermal insulation capacities.

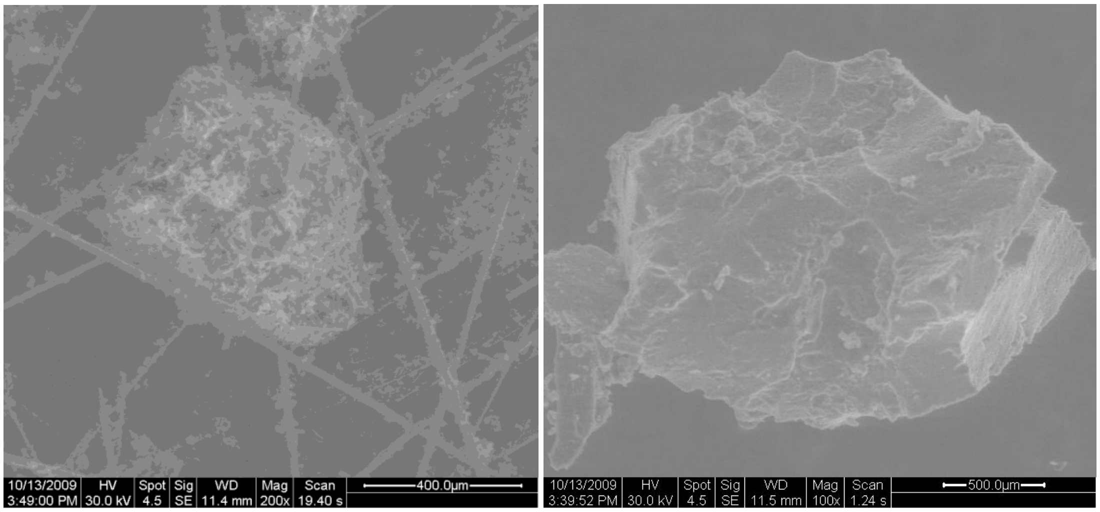

**Fig. 4. SEM of (a) Shredded Roofing Shingle and (b) Crumb Rubber Particle.**

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