Fiber-Reinforced Ceramic Tile

The addition of wollastonite fibers results in thinner, lighter and stronger ceramic tile than that produced using a conventional process.

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The weight of ceramic tile can be decreased by increasing its specific strength. Strength-decreasing flaws form within tile during either processing or service. Therefore, resistance to crack propagation is essential to the safe use of ceramic tile. The strength and toughness of ceramic tile have to be improved. Tile with improved mechanical performance can be thinner and lighter. The advantages of using thinner tile other than weight decrease are demonstrated.

The strength of triaxial bodies with clay–quartz–feldspar formulations has experienced intensive investigation for many years.[1–3] The strength of triaxial bodies depends strongly on the size of quartz particles and amount of mullite. The quartz particles must be kept under a critical size to avoid spontaneous cracking because of the phase transformation of quartz during cooling.[1] Clay transforms to mullite at elevated temperatures, then reacts with quartz and glassy phase to form secondary mullite.[4]

The increase of mullite content enhances tile strength.[3] However, secondary mullite forms at a relatively high temperature, and, thus, its content is relatively low within tile produced using the conventional fast-firing process. Although strength improvement of triaxial bodies has attracted considerable attention, toughness enhancement has received little attention. However, to ensure the safety of using ceramic-tile products with decreased weight, crack resistance is essential to reliability.

Addition of Fibers to Improve Toughness

The addition of second-phase particles that have a large aspect ratio to a ceramic matrix can improve its toughness.[5,6] The second phase can interact with cracks, provided the integrity of the second phase is preserved after firing in the presence of a glassy phase. Short-fibers, such as alumina and silicon carbide, have been incorporated into various ceramic matrices, and toughness improvement has been reported.[5,6]

The cost of alumina and silicon carbide fibers hinders their applications for ceramics. However, there are many mineral materials, either natural or synthetic, that exhibit fibrous form. In the present study, a natural mineral, wollastonite, is used for its fibrous form to enhance the mechanical performance of ceramic tile.

It is important to maintain the fiber form of wollastonite crystals. Therefore, a light mixing and rolling technique has been developed to prepare the fiber-reinforced tile.

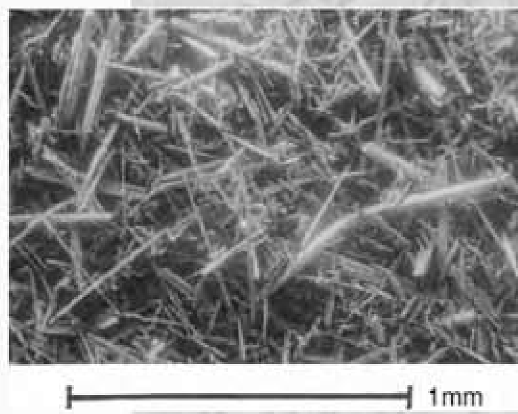

Fig. 1. Morphology of wollastonite grains used in tile production.

Fiber-Reinforced Tile Preparation and Testing

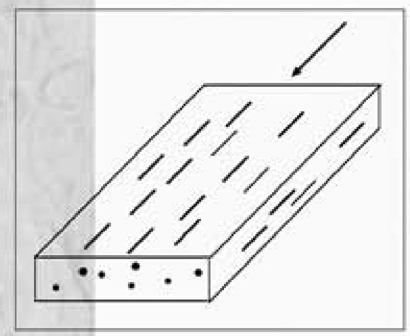

Fig. 2. Schematic of the fiber-reinforced tile. Arrow indicates the rolling direction.

Wollastonite powders were mixed for 10 min, then mixed for another 10 min after the addition of 20 wt% water. The semiwet feedstock was pressed several times using stainless steel rollers to achieve the dimensions of 2000 × 1100 × 4 mm. The wollastonite fibers tended to align with each other after repeated rolling. The problem of fiber tangling also was solved at this time. The green body was fired at a peak temperature at 1100°C.

Conventional ceramic tile also was prepared for comparison purpose. The tile was processed using the conventional route; that is, the powder mixtures were milled, sprayed dried, dry-pressed and sintered at 1050°C.

Rectangular bars with the dimensions of 40 × 5 × 3.5 mm (for fiber-reinforced tile, CERABO™) and 40 × 8 × 6 mm (for conventional tile) were cut from the tile using a diamond saw. The long dimension of the fiber-reinforced bar was parallel to the preferred orientation of the elongated wollastonite grains.

The flexural strength was determined using the four-point bending technique with spans of 10 and 30 mm. The

Table I. Composition and Original Dimensions of Fiber-Reinforced and Conventional Tile

Composition and dimensions	Fiber-reinforced tile	Conventional tile
Composition (wt%)		
Wollastonite	40	
Talc	10	10
Clay	30	30
Feldspar		40
Other	20	20
Original dimensions (mm)	1800 × 900 × 3.5	300 × 300 × 6

Table II. Basic Properties of Fiber-Reinforced and Conventional Tile

Property	Fiber-reinforced tile	Conventional tile
Density (g/cm^3)	1.9	2.0
Water adsorption (wt%)	12	6
Elastic modulus (GPa)	35	85

Table III. Strength, Weibull Modulus and Toughness of Fiber-Reinforced and Conventional Tile

Parameter	Fiber-reinforced tile		Conventional tile	
	Without glaze	With glaze	Without glaze	With glaze
Average strength (MPa)	36	45	21	23
Weibull modulus	14	13	9.2	7.6
Toughness (MPa·m$^{1/2}$)	2.0 ± 0.2		1.0 ± 0.1	

loading rate was 0.5 mm/min. More than 25 specimens were used to determine the Weibull modulus. The effect of glaze on strength also was evaluated. The toughness was determined using the single-edge notched-beam (SENB) technique. A notch with a depth of about one-half of the specimen thickness was generated using a thin diamond saw. The width of the notch was ~0.3 mm.

Tile Strength and Toughness Improved

The strength and toughness of the fiber-reinforced tile is almost two times that of the conventional tile. The Weibull modulus of the fiber-reinforced tile also is significantly higher than that of the conventional tile. The fracture surface of the fiber-reinforced tile reveals the presence of fibrous grains, although pores also are observed within the elongated grains.

Wollastonite can react with clay to form a liquid phase during sintering.[7] However, the fiber-reinforced tile is fired using the conventional fast-firing practice. Therefore, the wollastonite retains its crystallographic and fibrous form until the end of the sintering process. However, part of the calcium is dissolved into the liquid.

The application of glaze further enhances the strength of fiber-reinforced and conventional tile. However, the Weibull modulus of glazed tile is similar to that of the unglazed tile. This indicates that the flaw-size distribution within the tile is not changed by glaze application. The flaws mainly locate within the ceramic tile. The strengthening effect of the glaze is caused by the residual compressive stress it introduces to the tile.

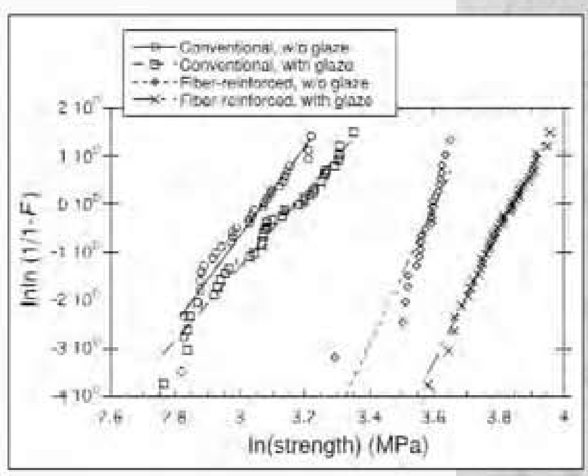

Fig. 3. Weibull plots for fiber-reinforced and conventional tile.

The porosity in the fiber-reinforced tile is higher than that in the conventional tile. The toughness of ceramic tile decreases with increases of porosity.[8] Therefore, the toughening effect is mainly contributed by the addition of elongated grains.

The advantages of strength and toughness improvement can be fully realized by decreasing tile thickness. The weight of the thin fiber-reinforced tile is ~60% that of the conventional tile of an equal area. Furthermore, because of its relative high porosity and decreased thickness, the thin fiber-reinforced tile can be machined using conventional metal-working tools.

In summary, conventional tile are produced using spray-drying and dry-pressing techniques. The clay-containing powder mixtures form strong agglomerates after drying. The pressure applied by dry pressing usually fails to destroy the agglomerates. Therefore, the strength of conventional tile is low and the strength scatter is large.

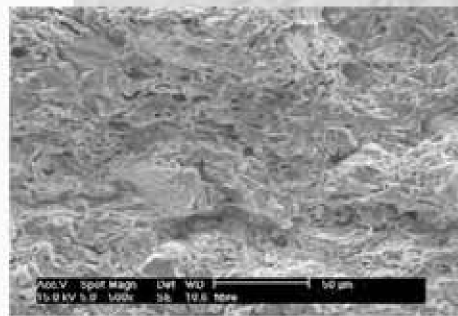

Fig. 4. Fracture surface of fiber-reinforced tile.

The addition of mineral fibers enhances the toughness of ceramic tile when a suitable fiber-processing route is applied. The rolling process used to prepare thin fiber-reinforced tile prevents agglomerate formation. Furthermore, the elongated grains are aligned during the rolling of the semiwet feedstock. The sizes of flaws in the fiber-reinforced tile are small; therefore, the strength of the tile is enhanced. The rolling process developed in the present study also decreases flaw-size distribution; therefore, the Weibull modulus of the fiber-reinforced tile also is high. ■

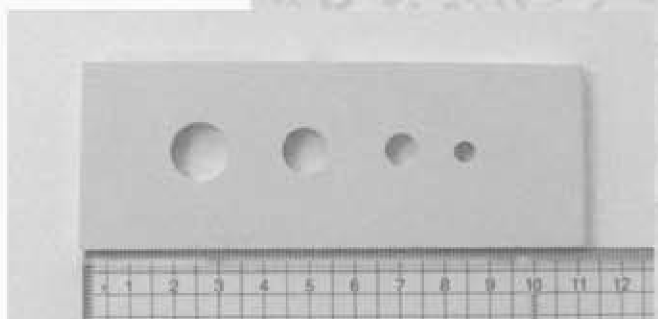

Fig. 5. Holes produced using surface-hardened metallic drill.

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