リサイクル骨材を用いたセメント複合材の強度とヤング率について
(Strength and Young's Modulus of Cement Composites with Recycled Aggregate)

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Introduction: It is well known that the utilization of the recycled materials such as concrete, stone, broken pavement, brick, gypsum and wood chips have tremendous benefit to the environment and significant cost saving in material acquisition and disposal. One idea gaining much attention is that of the use of recycled aggregate for the manufacture of cement-based composite materials for two environmental aspects mainly such as solving the waste storage problem and protection of limited natural sources of aggregate. To fully understand the behavior of these kinds of composites; four specimens for each category of recycled aggregate such as concrete, brick, stone, and wood chips along with 4 plain mortar specimens were prepared and tested. For all the specimens, the volume fraction of aggregate was 30 percent of the overall volume of specimens except the plain mortar specimens. Results of compression and tensile splitting tests of recycled-aggregate-cement-composite cylinders of size 10 mm in length and 5 mm in diameter are depicted. Comparison of the mechanical properties of the recycled-aggregate-cement composites such as compressive and tensile strengths, Young's modulus and unit weight are made and pertinent discussion regarding the investigated parameters is reported in this paper.

Materials and Method: The recycled aggregate of stone, brick and concrete were collected from the reconstruction site of Mie University, Japan and were broken by hammer to the desired size for obtaining suitable cement-based composite materials. The recycled wood chips were collected from the Wood Research Laboratory of Mie University, Japan and the required sizes were made by cutting them to smaller pieces. In order to obtain a uniformity of the cement composite with various types of aggregate, recycled aggregate having fineness modulus of 4.35 were used in casting process for all the specimens. The properties of recycled aggregate such as Young's modulus, Poisson's ratio and unit weight are summarized in **Table 1**. Ordinary Portland cement and river sand passing through a No.8 (2.38mm) sieve, which has a fineness modulus of 2.33, were used for casting. For all the specimens, the water to cement ratio and cement to sand ratio both were 0.5 by weight. The specimens were air-dried for 24 hours for initial setting and then immersed in water for curing. The specimens were removed from water after 7 days and were air-dried for 3 days in room temperature of about 15$^{\mathrm{o}}$ C and relative humidity of about 40%; then the tests were performed.

Table 1. Materials properties

Recycle	E(kN/mm^2)	v
Concrete	30	0.28
Stone	40	0.25
Brick	15	0.2
Wood	10	0.35

All the specimens were tested with a 1962kN capacity hydraulic avery type testing machine. The maximum capacity of the machine was adjustable to reduce scale and was set to 196.2 kN. The readings were taken initially at intervals of 9.81 kN and subsequently at 4.905 kN. The displacements of elements end compression for the compressive tests were measured with dial gauges having a least count of 0.01 mm. A careful attention was taken to eliminate the effect of end restraint of the test specimens. The tensile strengths were measured by splitting the cylinder specimens. The tensile strength was calculated according to ASTM C496 using Eq.1, where f_t is the tensile strength in N/mm^2, P is maximum applied load in Newton, L is the length of cylinder in millimeters and D is the diameter of cylinder in millimeters.

$$f_t = \frac{2P}{\pi DL} \quad \text{---} \quad (1)$$

Results and discussion: Properties of the cement composites such as Young's moduli, compressive strengths, unit weights and splitting tensile strengths with different recycled aggregate obtained from the laboratory experiment are given in **Table 2**. The values of the individual specimens presented in **Table 2** show that the Young's moduli, compressive strengths, unit weights and splitting tensile strengths of the composites vary with type of aggregate as well as within the composites of same aggregate.

Relationships between f_c' and E :

According to the test method of ASTM C469, the laboratory tests were carried out and the Young's modulus was calculated from the stress strain relationships by avoiding the nonlinearity at the initial and final loading conditions using Eq.2 where E is the modulus of elasticity, σ_1 is the stress corresponding to strain of 0.00005, σ_2 is the stress corresponding to 40% of ultimate strength and ε_2 is the strain produced by stress σ_2.

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.00005} \quad \text{---} \quad (2)$$

Based on the regression analysis, the relationship between the compressive strengths and the Young's modulus is obtained as given in Eq.3.

$$E = \alpha\,(f_c')^{1/2} \quad \text{---} \quad (3)$$

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Here, E is Young's modulus of composite in MPa, f_c' is the compressive strength of composite in MPa, α is the constant which has values of 1963, 1593, 1493, 1460 and 723 for composites of plain mortar, stone, brick, concrete and wood aggregate, respectively. It is noted here that the empirical relationship between the compressive strength and the Young's modulus of recycled aggregate concrete by the ACI code is given as Eq.4.

$$E = 33\gamma^{3/2}\,(f_c')^{1/2} \quad \text{--- (4)}$$

where γ is the unit weight of concrete in pound per cubic feet. This equation is the well known form for normal weight concrete with γ value of 145 pound per cubic feet, which is written as Eq.5.

$$E = 57000\,(f_c')^{1/2} \quad \text{--- (5)}$$

The Eq.5 by the ACI code can be rewritten in SI unit as of Eq.6.

$$E = 4734\,(f_c')^{1/2} \quad \text{--- (6)}$$

where, Young's modulus (E) and compressive strength (f_c') are in MPa. The α values of Eq.5 obtained in this research are smaller than the coefficient of Eq.6 given by ACI indicates the proposed equation provides conservative estimation of the Young's modulus of the cement composites containing recycled aggregate which agrees with the results of other researchers found in the literature (1,2). It is obvious that the α values vary depending on the type of recycled aggregate owing to different bonding phenomena and various Young's moduli of recycled aggregate.

Table 2. Properties of composites with different aggregate

	E(kN/mm^2)	f_c' (N/mm^2)	γ(t/m^3)	f_t (N/mm^2)
Mortar(1)	13.40	44.74	2.09	4.88
Mortar(2)	13.20	45.10	2.16	4.36
Mortar(3)	13.10	45.00	2.05	4.82
Mortar(4)	13.30	47.38	2.12	4.78
Stone(1)	10.50	37.46	1.98	4.36
Stone(2)	09.10	33.41	1.93	4.17
Stone(3)	08.90	34.42	1.92	4.22
Stone(4)	09.30	35.42	1.96	4.29
Brick(1)	09.10	34.85	1.97	4.25
Brick(2)	10.10	33.25	1.95	4.10
Brick(3)	09.20	35.26	1.97	3.90
Brick(4)	06.50	33.41	1.96	4.50
Concrete(1)	08.20	38.66	1.99	4.05
Concrete(2)	08.40	37.46	1.98	3.80
Concrete(3)	09.50	36.27	1.97	3.60
Concrete(4)	09.40	35.43	1.96	3.75
Wood(1)	02.60	09.10	1.59	1.65
Wood(2)	02.40	11.08	1.63	1.83
Wood(3)	02.30	09.11	1.59	1.60
Wood(4)	01.30	11.13	1.64	1.88

Relationships between the f_c' *and* f_t:

By performing the regression analyses of the experimental data, the relationship between the splitting tensile strength and the compressive strengths can be written as Eq.7.

$$f_t = \beta\,(f_c')^{1/2} \quad \text{--- (7)}$$

where, f_t is the splitting tensile strength in MPa, f_c' is compressive strength in MPa and β is an empirical constant which takes the values of 0.69, 0.70, 0.72, 0.62 and 0.54 for composite of plain mortar, stone, brick, concrete and wood aggregate, respectively. It should be pointed out here that the ACI code used for estimating the splitting tensile strength is given in Eq.8.

$$f_t = 0.56\,(f_c')^{1/2} \quad \text{--- (8)}$$

where, f_t is the splitting tensile strength in MPa and f_c' is compressive strength in MPa. It is evident that the ACI equation of recycled aggregate concrete underestimates the splitting tensile strength from the compressive strength in the case of plain mortar, stone, brick, concrete aggregate-cement composites whereas it overestimates the splitting tensile strength in the case of wood-aggregate composites.

Conclusions: In designing a structure with cement-based composite materials where both the strength and weight are needed to be taken into account, cement composites with recycled concrete aggregate may be recommended for better strength and lighter weight. On the other hand, for construction of light weight cement-based composite structure such as partition wall where strength is not a great factor, cement composites with wood aggregate may be used. Among the four types of recycled aggregate tested, the wood aggregate appears to be more effective for production of light weight composites where the recycled-concrete aggregate seems to be better for manufacturing a composite of higher Young's modulus and strength. Equations for estimating the Young's modulus and splitting tensile strength from the compressive strength can be used in generating conservative results.

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