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The relationships between stress and strain for high-performance concrete with metakaolin

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Abstract

This paper reports the results of a study of stress–strain relationships (tension and compression) and bend strength measurements for concrete incorporating 0%, 5%, 10%, and 15% metakaolin. The test results show that the tensile strength and peak strain increase with increasing metakaolin content whereas the tensile elastic modulus shows only small changes. The descending area of overpeak stress is improved when 5% and 10% of cement is replaced by metakaolin. Also, the bend strength and compressive strength increase with increasing metakaolin content. The compressive elasticity modulus of concrete shows a small increase with increasing metakaolin replacement. The compressive strength increases substantially at early ages, and there is also higher long-term strength. Therefore, the metakaolin is a very efficient strength-enhancing addition. The workability of concrete is little influenced by small metakaolin contents (5% metakaolin). At higher metakaolin contents workability can be controlled effectively by superplasticizer additions.

Keywords: Relationships of stress and strain; Concrete; Metakaolin; Elastic moduli

1. Introduction

Metakaolin recently has been introduced as a highly active and effective pozzolan for the partial replacement of cement in concrete. It is an ultrafine material produced by the dehydroxylation of a kaolin precursor upon heating in the temperature range of 700–800 °C [1]. Metakaolin is a silica-based product that, on reaction with $Ca(OH)_2$, produces CSH gel at ambient temperature. Metakaolin also contains alumina that reacts with CH to produce additional alumina-containing phases, including C_4AH_{13}, C_2ASH_8, and C_3AH_6 [2,3].

Research results have shown that the incorporation of metakaolin in concrete significantly enhances early strength [4]. Metakaolin increases resistance of concrete to alkali–silica reaction [5], and its effect on sulfate resistance increases systematically with increasing replacement of cement by metakaolin [6]. Energy absorption or toughness of high-performance steel-fiber-reinforced concrete increases with the introduction of high-reactivity metakaolin into the mix. Therefore, for applications where both enhanced durability and high toughness are required, the use of high-reactivity metakaolin concrete may be advantageous [7]. However, other research has also shown that increasing replacement levels of metakaolin produce increasing water demand, although this can be adjusted by adding a water reducer or blending the metakaolin with PFA to maintain the workability or flow properties [8].

The mechanical properties of concrete, including compressive strength, bend strength, and splitting–tensile strength, can be enhanced significantly up to 90 days by incorporation of metakaolin, and still show improvement at more than 1 year [4,6]. This enhanced performance is due to the filler effect, the acceleration of Portland cement hydration, and the pozzolanic reaction of metakaolin with CH [6–8].

In this paper, stress–strain behavior of metakaolin concrete in compression and in tension and the bend strength of metakaolin concrete are related to metakaolin content (at cement replacement levels of 0%, 5%, 10%, and 15% metakaolin). Furthermore, the compressive elastic modulus

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Table 1
Composition of metakaolin

	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	K_2O+Na_2O	Loss
Metakaolin	48.45	44.17	0.10	0.13	0.64	0.05	0.90

and workability with different metakaolin contents are discussed. To maintain constant concrete workability, superplasticizer has been added.

2. Experimental

2.1. Materials and mix proportion

The materials used were as follows: Type I Portland Cement. The metakaolin was supplied by HK Building Materials Ltd. The specific surfaces were 350 m^2/kg for cement and 12,000 m^2/kg for metakaolin. The average particle diameters were 8.27 μm for cement and 2.23 μm for metakaolin. The composition of metakaolin is listed in Table 1. The sand used was natural river sand with a fineness modulus of 2.3; the coarse aggregate was crushed limestone with a maximum size of 15 mm. The superplasticizer used was KFDN, which is a naphthalene sulfonate-based powder produced by Shenzhen ZSSC. To delay setting time and decrease the slump loss of the concrete, 0.25% retarder D-17 (as percent by weight of binder) was added to each mix. Replacement levels of PC by metakaolin chosen for the concrete mixes were 0%, 5%, 10%, and 15% and the water-to-binder (W/B) ratio used was 0.38. The mixture proportions based on a constant mixture volume of 1 m^3 are given in Table 2.

2.2. Specimen preparation

To disperse the metakaolin uniformly and improve the interfacial zone between the paste matrix and the coarse aggregate, the superplasticizer was dispersed in mixing water. The cement, metakaolin, sand and coarse aggregate, and part of the water were mixed for 2 min, and then the remaining water was added and mixing continued for another 2 min. A slump test was immediately carried out on fresh concrete, the concrete specimens were cast for compressive tests (cylinder, Ø 100 × 200 mm), for bend tests (beam, 400 × 100 × 100 mm), and for tensile tests (plate, 300 × 100 × 20 mm). The samples were demolded after 24-h and stored in a curing room at 23 ± 3 °C and with a 100% relative humidity.

Table 2
Mixing proportion of concrete (kg/m^3)

Materials	C	S	G	W	KFDN	D-17	MK
MK0	426	720	1080	162	4.26	1.06	0
MK5	405	720	1080	162	4.26	1.06	21
MK10	383	720	1080	162	4.26	1.06	43
MK15	362	720	1080	162	4.26	1.06	64
MKS10	383	720	1080	162	4.69	1.06	43
MKS15	362	720	1080	162	5.11	1.06	64

W/B = 0.38; sand ratio Sp = S/(S + G) = 40%
C = Cement; S = river sand; G = coarse aggregate; W = water; KFDN = superplasticizer; D-17 = retarder; MK = metakaolin.

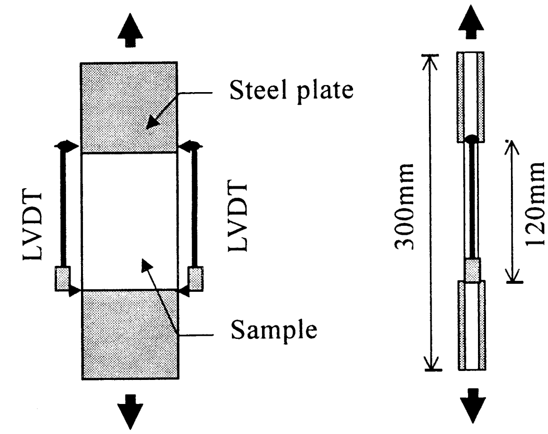

Fig. 1. The setup for uniaxial tension test of concrete.

2.3. Tensile test

After curing, each end of the tensile specimen was glued onto two steel plates that were connected to loading fixtures by pins. The loading fixtures were connected to MTS hydraulic grips. On each side of the specimen, one LVDT (linear variable differential transducer) was attached to measure the deformation of a specimen. These two LVDTs were connected to the digital controller of the MTS machine through two AC conditioners. The average output of the two LVDTs was used as a feedback signal to form a closed-loop control. To include cracks at the boundary of the steel plate and the test portion of the specimen, the span of the LVDT was slightly extended beyond the boundary (see Fig. 1). To

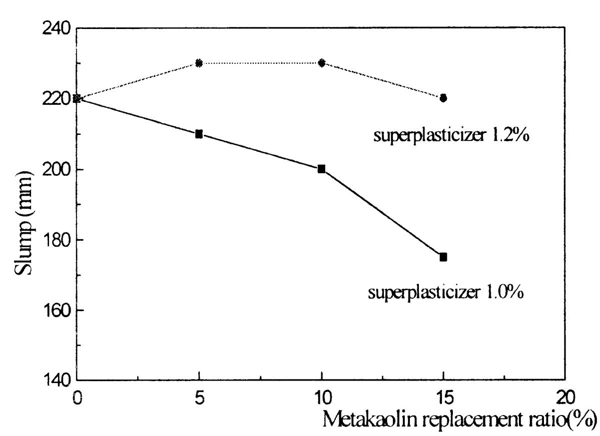

Fig. 2. Relationships of slump with metakaolin replacement.

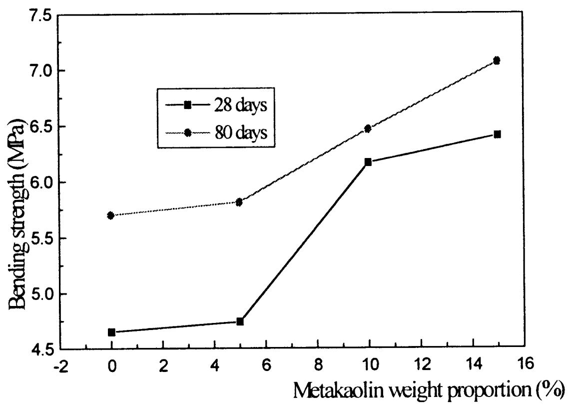

Fig. 3. Relationships of bending strength with metakaolin replacement.

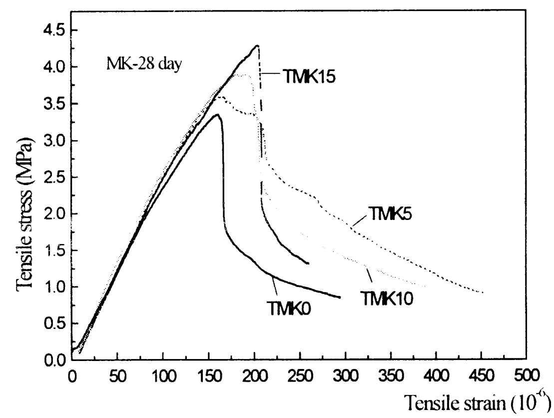

Fig. 4. Relationships between tensile stress and strain of concrete with different metakaolin (MK) replacement.

ensure proper alignment of the LVDT and friction-free movement of the electric core, preload checking was performed. The uniaxial tension tests were conducted at a displacement rate of 0.003 mm/min. The data of load and deformation were recorded directly by a computer.

2.4. Bend test

After curing, the 400 × 100 × 100-mm beam specimens were tested in four-point bend on a span of 300 mm in accordance with ASTM C1018, employing an MTS machine. One LVDT was mounted on the base of the specimen at the midspan. The bend test was conducted at a mid deflection displacement rate of 0.006 mm/min. The data of load and deformation were recorded directly by a computer.

2.5. Compression test

The cylinders, before testing, were capped with sulfur blinder on their two opposite faces. Then, one ring displacement controller was connected to the middle of the specimen. An LVDT was attached to each side of the specimen to measure its deformation. These two LVDTs were connected to the digital controller of the MTS machine through two AC conditioners. The average output of the two LVDTs was used as a feedback signal to form a closed-loop control. The uniaxial compression tests were conducted at circle displacement rate of 0.0006 mm/s. The data of load and deformation were recorded directly by a computer.

3. Results and discussion

3.1. Workability of fresh concrete

Fig. 2 shows the relationship between the metakaolin content and the slump value in fresh concrete. For concrete with a 1% superplasticizer addition, the slump progressively decreases with increasing metakaolin content. However, by increasing the superplasticizer dose to 1.2%, the slump showed only minor variation with increasing metakaolin content.

3.2. Bend strength

Fig. 3 and Table 3 show the bend test results for the concrete. A metakaolin replacement level of 5% has little effect on the bend strength of the concrete. At 10% and 15% replacement, the 28-day bend strength increases by, respectively, 32% and 38%. Even at 80 days, the bend strength of the concrete increases by, respectively, 13% and 24% in relation to that without metakaolin. Therefore, significant improvement in bend strength of concrete can be achieved for replacement levels of 10–15% metakaolin.

Table 3
Bending strength with different metakaolin replacement (MPa)

	MK0		MK5		MK10		MK15	
Age (days)	Average strength	Relative strength	Average strength	Relative strength	Average strength	Relative strength	Average strength	Relative strength
28	4.65	1.00	4.74	1.02	6.16	1.32	6.40	1.38
80	5.70	1.00	5.81	1.02	6.46	1.13	7.06	1.24

Table 4
Tensile strength with different metakaolin replacement (MPa)

	MK0		MK5		MK10		MK15	
Age (days)	Average strength	Relative strength	Average strength	Relative strength	Average strength	Relative strength	Average strength	Relative strength
28	3.35	1.00	3.58	1.07	3.88	1.16	4.29	1.28

3.3. Tensile properties

Fig. 4 shows the tensile stress–strain relationships for 28-day cured concrete. The tensile strengths are listed in Table 4.

The results show that tensile strength of concrete increases systematically with increasing metakaolin replacement level. The average tensile strength increases are 7% (5% metakaolin), 16% (10% metakaolin), and 28% (15% metakaolin), and the average ultimate strain increases are 3% (5% metakaolin), 19% (10% metakaolin), and 27% (15% metakaolin). The descending area of overpeak stress is less steep when metakaolin replacement is 5% and 10% whereas with 15% metakaolin it is similar to that for concrete without metakaolin. The tensile elasticity modulus for these specimens is in the range from 26 to 27 GPa. Also, the relationship between tensile strength and metakaolin content is similar to that of bend strength and metakaolin content.

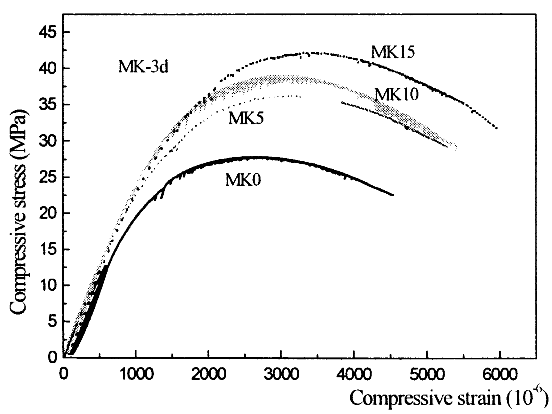

Fig. 5. Relationships between compressive stress and strain of concrete with different metakaolin (MK) replacement.

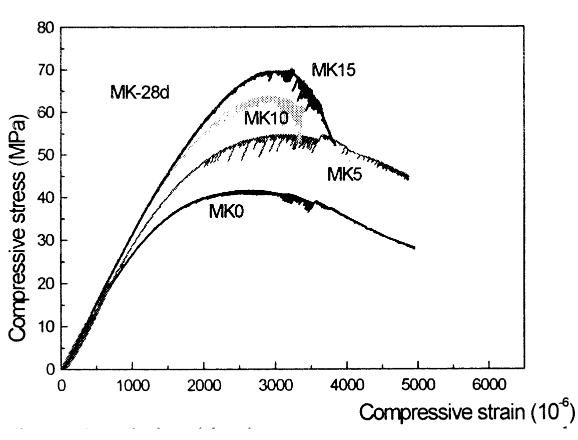

Fig. 6. Relationships between compressive stress and strain of concrete with different metakaolin (MK) replacement.

3.4. Compressive properties

Figs. 5–7 show the stress–strain relationships for concrete at different ages. The strength, elastic modulus, and peak strain at different metakaolin replacements and at different ages are listed in Table 5. The compressive strength increases substantially with increase in metakaolin content. Especially at 3 days curing, it increases 51% with 15% metakaolin replacement relative to concrete without metakaolin. Furthermore, the 3-day strength with 10% and 15% metakaolin replacement are larger than the 28-day strength without metakaolin, confirming that metakaolin has a pronounced influence on early strength.

Also, the elasticity modulus increases with increase in metakaolin replacement, but the rate of increase is less than that for the compressive strength. The ratios of tensile strength to compressive strength and bend strength to compressive strength are listed in Table 6. It shows that both ratios decrease with increasing metakaolin replacement. This indicates that the brittleness of concrete increases with increasing metakaolin replacement.

4. Conclusions

1. The tensile, bend, and compressive strength of concrete increase with increasing metakaolin content

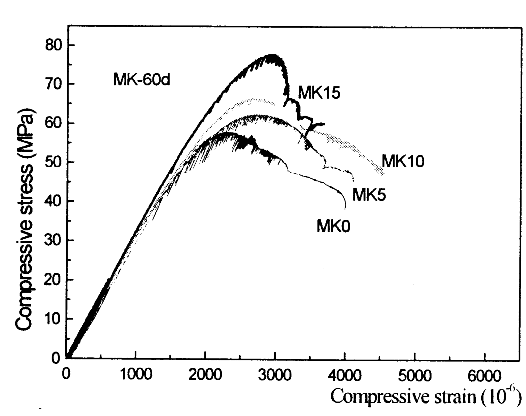

Fig. 7. Relationships between compressive stress and strain of concrete with different metakaolin (MK) replacement.

Table 5
Average strength, elasticity modulus, and peak strain with different metakaolin replacement

	Average strength (MPa)			Average peak strain ($\times 10^{-6}$)			Average elastic modulus (GPa)		
Ages	3 days	28 days	60 days	3 days	28 days	60 days	3 days	28 days	60 days
MK0	27.9	37.8	58.0	2646	2398	2333	24.1	30.0	30.4
MK5	36.3	45.7	62.4	2951	2776	2763	25.6	31.5	33.1
MK10	39.1	63.8	66.5	3037	2873	2648	26.0	33.2	34.4
MK15	42.2	69.7	77.8	3393	3052	2977	26.2	33.2	34.7

Table 6
Ratios of tensile/compressive and bending/compressive strength

	MK0		MK5		MK10		MK15	
	Ratio	Relative ratio	Ratio	Relative ratio	Ratio	Relative ratio	Ratio	Relative ratio
Tensile/compression strength	0.087	1.00	0.078	0.90	0.061	0.70	0.062	0.71
Bend/compression strength	0.123	1.00	0.104	0.85	0.097	0.79	0.092	0.75

especially at the early age. The tensile and compressive peak strain also increase with increasing metakaolin content.

2. The compressive elasticity modulus of concrete shows only small increases with increase in metakaolin content.
3. The ratios of tensile to compressive strength and bend to compressive strength decrease with increasing metakaolin content. This indicates that the brittleness of the concrete increases with increasing metakaolin content.

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