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Influence of Mixture Condition and Moisture on Tensile Strain Capacity of Concrete

Sontaya Tongaroonsri and Somnuk Tangtermsirikul*

School of Civil Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University, Patumthani 12121, Thailand.

* Corresponding author, E-mail: somnuk@siit.tu.ac.th

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ABSTRACT: The effect of water to binder (w/b) ratio, paste content, type of cement, content of mineral admixtures, aggregate maximum size (G_{max}), sand content, and presence of moisture on the tensile strain capacity, or cracking strain, of concrete were investigated using flexural test method. The investigation showed that the effect of cement type, paste content and sand content in the tested ranges was not significant. The cracking strain decreased with the increase of the w/b ratio, and replacement ratio of fly ash and limestone powder. For ground granulated blast-furnace slag (GGBS), specimens containing 30% and 50% GGBS showed a higher cracking strain than that without GGBS, but at 70% GGBS, the cracking strain decreased. The cracking strain of concrete with a high w/b ratio (w/b=0.55) was the highest when G_{max} was 19 mm. However, when the w/b ratio was 0.30, there was a tendency that the cracking strain was the highest when G_{max} was 10 mm. The cracking strain increased whereas the flexural strength and splitting tensile strength reduced when concrete was oven-dried.

KEYWORDS: Tensile strain capacity, Cracking strain, Flexural strength, Fly ash, Slag, Limestone powder, Moisture.

INTRODUCTION

Cracking in concrete structures is usually caused by load, imposed deformation, temperature, shrinkage or their combination. Shrinkage cracking is a complex phenomenon which is dependent on several factors including free shrinkage, shrinkage rate, creep relaxation, modulus of elasticity, degree of restraint and tensile strain capacity or tensile strength of concrete[1]. Cracking due to shrinkage results in decreased durability because cracks allow ingress of water and aggressive chemicals into concrete, leading to accelerated corrosion of reinforcing steel. In the case of prestressed concrete system, shrinkage cracking is an important factor. Shrinkage leads to reduction of strain in the prestressing steel. This in turn contributes to prestressing loss in the system. Shrinkage cracking can take place either at early or later ages. Concrete has low tensile strain capacity at early age[2], which is the critical period for cracking. Later age shrinkage can result in cracks that are formed in the similar manner as those formed at early age. If shrinkage of concrete takes place without any restraint, concrete will not crack. However, concrete structures are always subject to a certain degree of restraint, for example by other parts of the structures or by the reinforcing steel embedded in the concrete. This combination of shrinkage and restraint induces restrained strain. When this restrained strain reaches the tensile strain capacity, the concrete cracks[3]. Another type of restraint is developed by the difference between shrinkage near the surface and the interior shrinkage of a concrete member. Since drying shrinkage is always larger at the exposed surface, the interior portion restrains the shrinkage of the surface concrete, thus developing non-uniform stress distribution along the depth of the member. This will cause surface cracking. Shrinkage, together with low tensile strength, are some of the disadvantageous properties of Portland cement concrete[4]. In some cases, an expansive agent is used to control shrinkage cracking of structure. Due to the high cost of an expansive agent, precise estimation of tensile strain capacity of concrete is useful for determining the optimum content of expansive agent for shrinkage crack control.

Tensile strain capacity is defined as the maximum tensile strain that concrete can withstand without crack forming. Based on the tensile strain capacity rather than the tensile strength, cracking can be more accurately evaluated. Most researchers have attempted to use either direct tension test[5,6,7,8] or flexural test[9,10,11] to study tensile strain capacity of concrete. However, tensile strain capacity is more conveniently evaluated from flexural test[10,11]. For direct tension test, uniform tensile stress occurs along the cross-section. In the case of flexural test, non-uniform stress distribution occurs along the cross-section of member. In the real structure, the stress distribution caused by drying shrinkage or temperature is usually not uniform across the section especially near the exposed surface. So, flexural test was selected for tensile strain capacity evaluation in this study.

Nowadays, many types of mineral admixture such as fly ash, ground granulated blast-furnace slag and limestone powder are widely used in concrete. However, there is limited information on the cracking properties of concrete containing these mineral admixtures. Many researchers[6,7,9,10] studied the effect of fly ash on tensile strain capacity of concrete. Most of these researches used fly ash to replace cement at 30%. While, in real application in Thailand, fly ash is used to replace cement from 10% up to 50%.

The objective of this study is to investigate the tensile strain capacity of concrete with various types of binder, mix proportion and moisture condition. The studied parameters were the water to binder (w/b) ratio, paste content, type of binder, content of mineral admixtures, aggregates maximum size, sand content, and moisture condition (wet and oven-dried).

Experimental Program

Materials and Mixture Proportions

The reference concrete mix was based on ordinary Portland cement (Type I). Type III Portland cement (High early strength Portland cement) and Type V Portland cement (Sulfate- resisting Portland cement) were used to study the effect of type of cement on cracking strain. The mineral admixtures used in this study were fly ash (FA), ground granulated blast-furnace slag (GGBS) and two types of limestone powder having fine grain (LPF) and coarse grain (LPC) with average particle size of 2 and 13 micron, respectively. Chemical compositions and physical properties of the powder materials are given in Table 1. Fine aggregates was river sand with a specific gravity of 2.60 and fineness modulus of 2.13. Crushed limestone coarse aggregates with maximum size of 19 mm and specific gravity of 2.74 was used in almost all test cases. Coarse aggregates with maximum size of 10 and 25 mm were also used to study the effect of the maximum size. The properties fine and coarse aggregates complied with ASTM C33-97.

Flexural test method, ASTM C 78-84 (third point loading), was used to determine the cracking strain of concrete. The parameters utilized for studying tensile strain capacity were the w/b ratio, maximum size of aggregates, sand to total aggregates ratio (s/a), type of cement, type of mineral admixture and moisture content. The w/b ratio was varied at 0.3 and 0.55. The weight percentages of cement replaced by fly ash were 0%, 30% and 50%. For GGBS, the replacement percentages were 0%, 30%, 50% and 70%. The replacement percentages of limestone powder were 10% and 20%. The oven-dried and wet specimens were used to study the effect of moisture content. Thirty four mixtures were designed based on the varied parameters and their mixture proportions were shown in Table 2.

Test Procedure

The prismatic specimens used for flexural tests had dimensions of 100x100x500 mm while the cylinder samples used for the compressive strength and splitting tensile strength tests had dimensions of f100x200 mm. Splitting tensile strength test, ASTM C 496-04, was also conducted to study the effect of moisture condition on tensile strength. The specimens were demoulded 24 hours after casting and cured in water until reaching the test ages. The specimens were tested at 1, 3, 7, and 28 days. The specimens for studying the effect of moisture content were prepared in two groups (wet specimens and oven-dried specimens). After being demoulded, the specimens were submerged in water at temperature about 24 ºC for 26 days followed by 2 days in an oven at 105 ºC to prepare the oven-dried specimens. The wet specimens were submerged in water for 28 days. Both groups were tested at the same age of 28 days. On the test day the surface of beam specimens were smoothened by using sandpaper for displacement transducer (PI gauge) attachment. Three PI gauges, having a 100-mm gauge length, were attached to the bolts glued on the tensile surface in the constant moment span of the beam specimen. The cross-section of each specimen was measured before the test. Figure

Table 1. Chemical compositions and physical properties of OPC, PFA, GGBS, LPF and LPC.

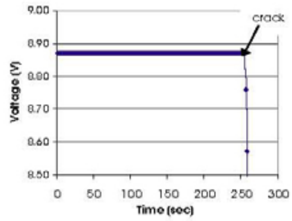
Material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	LOI (%)	Fineness (cm^2/g)	Specific gravity
OPC	20.20	4.70	3.73	63.40	1.37	1.22	-	0.28	2.72	3430[a]	3.11
GGBS	32.50	14.50	0.39	42.30	6.70	-	-	0.23	0.88	4060[a]	2.91
PFA	36.10	19.40	15.10	17.40	2.97	0.77	0.55	2.17	2.81	2460[a]	2.44
LPF	0.06	0.09	0.04	54.80	0.57	-	-	-	43.80	9260 [a]	2.70
LPC	0.27	0.18	0.08	54.30	0.62	-	-	-	43.63	3320 [a]	2.71

OPC, ordinary Portland cement; PFA, Pulverised Fuel Ash; GGBS, ground granulated blast-furnace slag; LPF, limestone powder having fine grain; LPC, limestone powder having coarse grain.
[a] Using Blaine's air permeability method.

1a shows the attachment of bolts on the beam surface. The layers of plastic sheet were used at the supports to reduce effect of friction between specimen and supports.

Crack was detected by using the voltage circuit. Two straight lines were drawn on the tensile surface of the beam specimen using a 6B carbon pencil. Then the two ends of the lines were connected to a circuit containing a 9-volt battery and connected to a data logger. Figure 1a shows the position of the PI gauges and the carbon lines. The use of pencil line to detect crack was also used in previous research[12]. The loading speed of testing machine was controlled at 1.8 MPa/min. Strain, voltage and load data were acquired through the use of a portable data logger. The data was recorded at every second. During data collecting, an abrupt change of voltage was observed when cracking had occurred as shown in Figure 1b.

(a) Position of PI gauges and carbon lines



(b) An abrupt change of voltage

Fig 1. Strain measurement and crack detector at tensile surface of the beam specimen.

Table 2. Mixture proportions.

Mix No.	Mix Designation	g	w/b	Percentage of replacement	Unit content (kg/m³) C	MA	W	S	G	Remark
1	γ1.4w3r0	1.4	0.30	-	495	0	148	772	1028	MC
2	γ1.2w3r0	1.2	0.30	-	422	0	127	823	1096	
3	γ1.4w3r30FA	1.4	0.30	30 (FA)	332	142	142	772	1028	MC
4	γ1.4w3r50FA	1.4	0.30	50 (FA)	231	231	139	772	1028	
5	γ1.4w4r0	1.4	0.40	-	426	0	171	772	1028	
6	γ1.4w4r30FA	1.4	0.40	30 (FA)	288	123	164	772	1028	
7	γ1.4w55r0	1.4	0.55	-	353	0	194	772	1028	MC
8	γ1.2w55r0	1.2	0.55	-	301	0	165	823	1096	
9	γ1.4w55r30FA	1.4	0.55	30 (FA)	240	103	188	772	1028	MC
10	γ1.4w55r50FA	1.4	0.55	50 (FA)	168	168	185	772	1028	
11	γ1.4w3r0T3	1.4	0.30	-	504	0	151	772	1028	Cement Type III
12	γ1.4w3r0T5	1.4	0.30	-	497	0	149	772	1028	Cement Type V
13	γ1.4w55r0T3	1.4	0.55	-	357	0	197	772	1028	Cement Type III
14	γ1.4w55r0T5	1.4	0.55	-	354	0	195	772	1028	Cement Type V
15	γ1.4w3r0G3/8	1.4	0.30	-	495	0	148	772	1028	G_{max} =10 mm
16	γ1.4w55r0G3/8	1.4	0.55	-	353	0	194	772	1028	G_{max} =10 mm
17	γ1.4w3r0G1	1.4	0.30	-	495	0	148	772	1028	G_{max} =25 mm
18	γ1.4w55r0G1	1.4	0.55	-	353	0	194	772	1028	G_{max} =25 mm
19	γ1.4w3r10 LPF	1.4	0.30	10 (LPF)	442	49	147	772	1028	MC
20	γ1.4w3r20 LPF	1.4	0.30	20 (LPF)	390	97	146	772	1028	
21	γ1.4w4r10LPF	1.4	0.40	10 (LPF)	381	42	169	772	1028	
22	γ1.4w55r10 LPF	1.4	0.55	10 (LPF)	316	35	193	772	1028	MC
23	γ1.4w55r20 LPF	1.4	0.55	20 (LPF)	279	70	192	772	1028	
24	γ1.4w3r10 LPC	1.4	0.30	10 (LPC)	442	49	147	772	1028	MC
25	γ1.4w3r20 LPC	1.4	0.30	20 (LPC)	390	97	146	772	1028	
26	γ1.4w4r10LPC	1.4	0.40	10 (LPC)	381	42	169	772	1028	
27	γ1.4w55r10 LPC	1.4	0.55	10 (LPC)	316	35	193	772	1028	MC
28	γ1.4w55r20 LPC	1.4	0.55	20 (LPC)	279	70	192	772	1028	
29	γ1.4w3r30SG	1.4	0.30	30 (GGBS)	343	147	147	772	1028	
30	γ1.4w3r50SG	1.4	0.30	50 (GGBS)	244	244	146	772	1028	
31	γ1.4w3r70SG	1.4	0.30	70 (GGBS)	145	339	145	772	1028	
32	γ1.4w55r30SG	1.4	0.55	30 (GGBS)	245	105	193	772	1028	
33	γ1.4w55r50SG	1.4	0.55	50 (GGBS)	175	175	192	772	1028	
34	γ1.4w55r70SG	1.4	0.55	70 (GGBS)	104	243	191	772	1028	

γ is the ratio between volume of paste and volume of voids of the densely compacted aggregate phase; w/b is the water to binders ratio; MC is the mixtures for studying effect of moisture content. G_{max} is the maximum size of coarse aggregate. For instance, γ1.4w3r30FA means γ=1.4, w/b=0.30, replacement ratio=30% by fly ash. C, MA, W, S, and G denote cement, mineral admixture, water, sand and coarse aggregate , respectively.

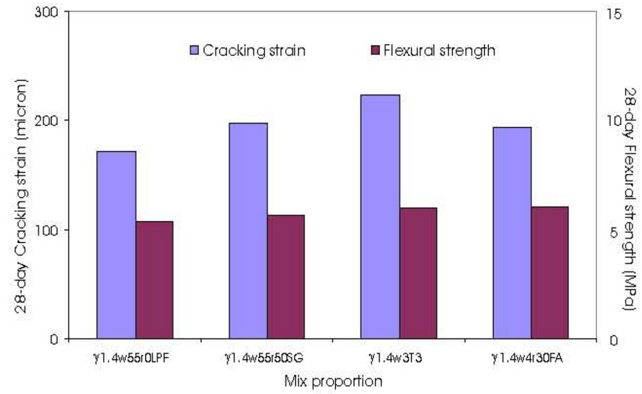
Results and Discussion

According to the test results in Figure 2a and Figure 2b, cracking strain of concrete varied with mix proportions and mineral admixtures. When compared at the same flexural strength, cracking strain varied with the type of mineral admixture (Figure 2a). This implies that the use of flexural strength, or may be similarly tensile strength, to evaluate the commencement of crack can be inaccurate especially for the crack control problem like that caused by restraining shrinkage where the load carrying capacity is not the major concern but the crack occurrence. The results showed that the cracking strain at 28 days was between 167 – 225 me. The similar test by Wee et al[6] showed cracking strain in the range of 150 – 210 me. The test results on effect of each parameter on cracking strain are discussed in the following sections.

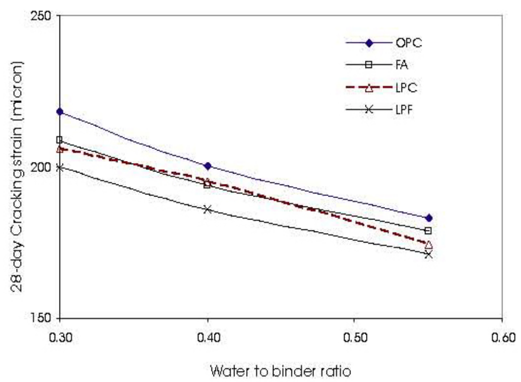
Effect of Age, Strength and Water to Binder Ratio

The fracture surfaces of concrete beams were visually examined after the beam specimens were fractured. The fracture surfaces together with the strength of concrete are usually used in primary observation of the quality of interfacial transition zone (ITZ) or bond between paste and aggregates[13,14,15]. Figures 3a and 3b show examples of two fracture surfaces of beams having the same mixture condition. One was tested at early age (lower strength) while the other was tested at later age (higher strength). It can be seen from Figure 3a that at early age the crack passed the interfaces between coarse aggregates and paste, while Figure 3b shows the situation of the crack cutting through the coarse aggregates when tested at later age. The propagation of the crack tip usually developed toward the weakest path (the path which requires the lowest crack propagation energy). The initiation and growth of crack would reduce the load carrying area. This reduction in area caused an increase in the stress concentration at the crack tips. For low bond strength, the crack tip developed along the interface between paste and aggregates. This led to rough surface. But for high bond strength, the crack tip could not grow along the interface because it had to use more propagation energy than to pass through coarse aggregates with a straight direction. This led to a more flattened fracture surface. Figure 3c shows that the crack path depended on flexural strength as a major parameter. Moreover, test results in Figure 3c show that the path of fracture surface, flexural strength and cracking strain had some correlation. When concrete had low strength, the crack passed the transition zone while at high strength, the crack cut through the aggregates. At intermediate strength, the crack passed both the transition zone and coarse aggregates. The behavior shown in Figure 3 indicates that the strength of paste and the quality of ITZ played an important role on the cracking strain of concrete. The ITZ strength depended on the strength of paste and the properties of aggregates (strength, shape and texture of aggregates)[15]. When the paste had low strength, the crack passed through the paste or ITZ, and in this case, the cracking strain depended mainly on the strength of paste and ITZ. When the strength of paste and therefore ITZ became stronger, the crack would pass through coarse aggregates and in this condition, the cracking strain depended not only on the strength of paste but also on the quality of coarse aggregates.

Figure 2b shows that, mixtures with a lower w/b ratio had a larger cracking strain than those with a higher w/b ratio. This was because concrete with a lower w/b had higher paste strength than that with a higher w/b ratio. Reducing the w/b ratio significantly increased the interfacial properties[16] and led to a high cracking strain.

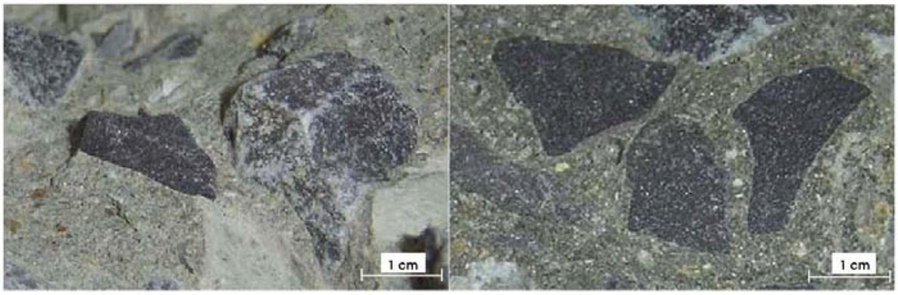


(a) Comparison of cracking strain and flexural strength

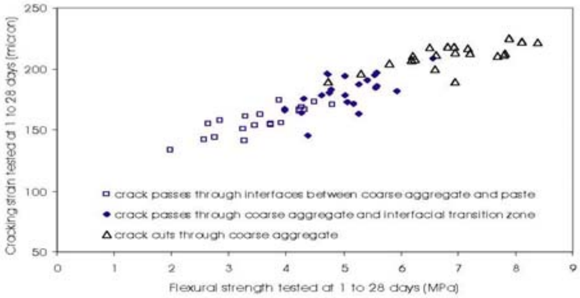


(b) Effect of water to binder ratio

Fig 2. Effect of mix proportions and water to binder ratio on cracking strain.



(a) Fractured surface at early age (lower strength) (b) Fractured surface at later age (higher strength)

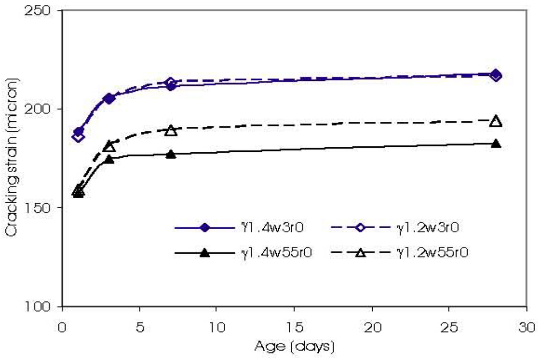


(c) Relationship between crack path and flexural strength

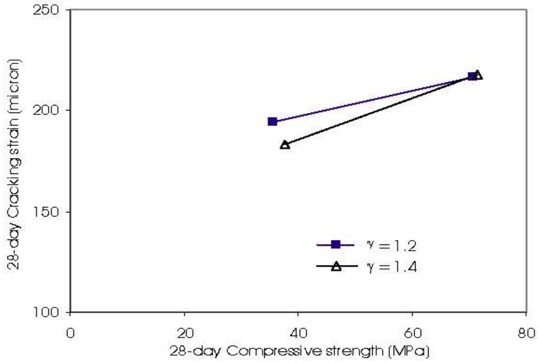
Fig 3. Relationship between crack path, cracking strain and flexural strength.

Effect of Paste Content

Figure 4a shows that the paste content had little effect on the cracking strain of low w/b concrete. For mixtures with a high w/b ratio, concrete with a lower paste content (γ=1.2) had a higher cracking strain than that with a higher paste content (γ=1.4). Figure 4b shows that the low strength concrete encountered more obvious effect of the paste content than the high strength concrete does. This was because at a low w/b ratio, the strength difference between paste and aggregates was not large and the crack cut mostly through the coarse aggregates. In this condition, aggregates content, which is the inverse of paste content, did not affect the cracking strain. On the other hand, for high w/b ratio concrete, the difference between the strength of paste and that of aggregates was relatively larger. The crack passed both the transition zone and coarse aggregates. In this condition, mixtures with a lower paste content, having a higher aggregates content, were provided with more



(a) Effect of paste content



(b) Compressive strength and cracking strain tested at 28 days

Fig 4. Effect of paste content on cracking strain.

aggregates particles with relatively higher resisting strength, and thus demonstrated a higher cracking strain[6,17].

Effect of Mineral Admixtures

Figure 5a and Figure 5b show that if comparing mixtures with similar parameter condition except for the type and content of mineral admixtures, the cracking strain of fly ash concrete is lower than that of the concrete without fly ash. This is due to the decreasing of paste strength because strength development of fly ash paste is slower than that of the paste without fly ash[18]. The cracking strain also decreases with the increasing of the replacement ratio of fly ash by the same reason.

For slag concrete, test results in Figure 5c show that the cracking strain of slag concrete was lower than that of cement-only concrete at early age. This was because strength of slag concrete was smaller than that of cement-only concrete at early age. The smaller strength led to reduction of tensile strength and strain capacity of slag concrete at early age[19]. At later age, the cracking strain of slag concrete was higher than that of the cement-only concrete. Figure 5d shows that the cracking strain increased with the increase of slag content up to an optimum content. The optimum content of slag for the largest cracking strain from the test results was about 50%. When slag content was 70%, the cracking strain tended to decrease especially in high w/b ratio mixtures.

Test results in Figure 5e and Figure 5f show that the cracking strain of limestone powder concrete was lower than that of the cement-only concrete especially for LPF. This may be due to the non-cementitious property of the limestone powders. However, it was still not clear as to why LPF mixtures showed inferior tensile strain capacity to LPC mixtures inspite of higher early age strength. Further studies are necessary to clarify this effect.

When compared at the same 28-day compressive strength as shown in Figure 6, the cracking strains of fly ash and coarse grain limestone powder concrete were about the same as that of the cement-only concrete.

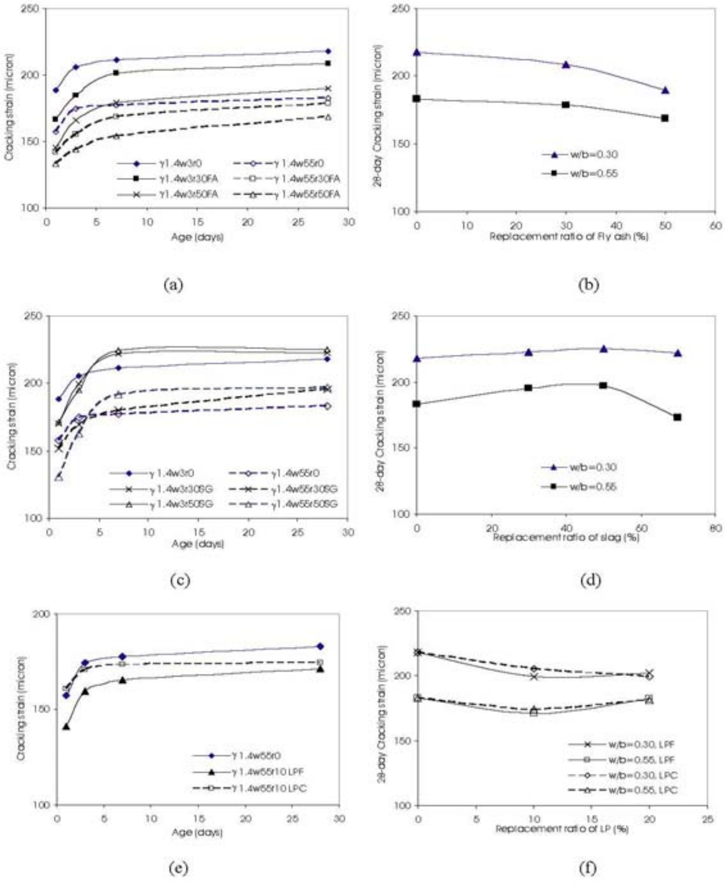


Fig 5. (a) Relationship between cracking strain and age of concrete (effect of fly ash). (b) Relationship between 28-day cracking strain and replacement ratio of fly ash. (c) Relationship between cracking strain and age of concrete (effect of slag). (d) Relationship between 28-day cracking strain and replacement ratio of slag. (e) Relationship between cracking strain and age of concrete (effect of limestone powder). (f) Relationship between 28-day cracking strain and replacement ratio of limestone powder.

The fine grain limestone powder concrete had a lower cracking strain than cement-only concrete while the cracking strains of slag concrete were higher. However, for the crack control it should be noted that the shrinkage cracking of concrete was related not only to the tensile strain capacity, but also to the amount of shrinkage, degree of restraint, modulus of elasticity and creep relaxation of concrete.

Effect of Cement Types

Three types of cement (Types I, III and V) were used to study the effect of cement types on the cracking strain. Figure 7a and Figure 7b show that when compared at the same w/b ratio, the cracking strain of cement type III concrete was slightly higher than that of the concrete made from cement type I and type V. Type V cement concrete showed the lowest cracking strain. The reason was because the rate of strength development of cement type III was the fastest, while that of the type V cement was the slowest. When compared at the same flexural strength (see Figure 7b), the cracking strain did not vary significantly with types of cement.

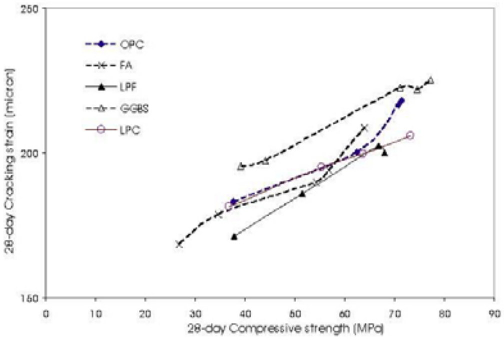
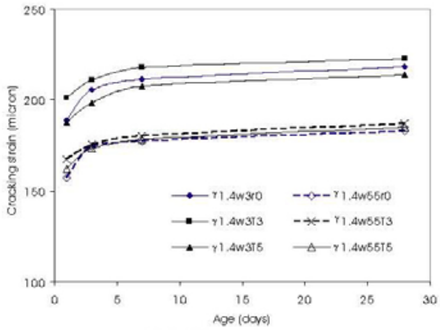
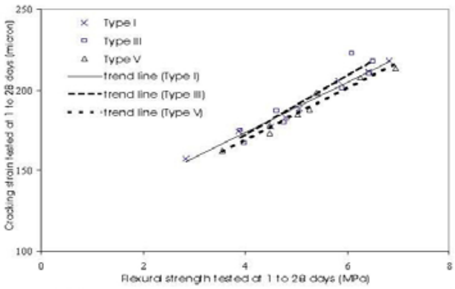


Fig 6. Effect of mineral admixtures on 28-day cracking strain.



(a) Effect of cement types

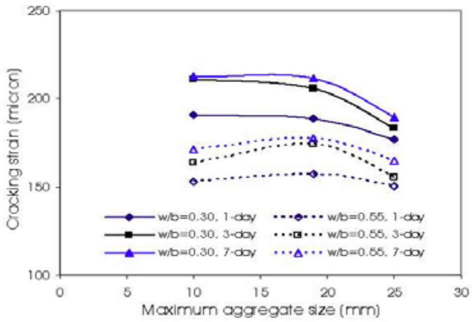


(b) Flexural strength and cracking strain tested at 1 to 28 days

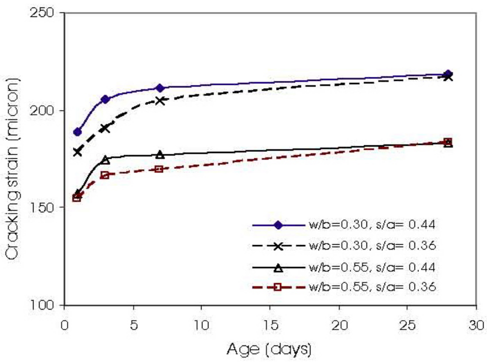
Fig 7. Effect of cement types on cracking strain.

Effect of Maximum Size of Aggregate and Sand to Total Aggregate Ratio

Three maximum sizes of aggregates (10, 19 and 25 mm) and two sand to total aggregates ratios (s/a = 0.36 and 0.44 by volume) were varied to study the effect of aggregates size and the s/a ratio on the cracking strain. Visual examination showed that smoother the crack surface was observed for specimens with smaller aggregates size, and rougher for those with larger aggregates size. Figure 8a shows that the cracking strain of the high w/b ratio concrete (w/b=0.55) was the highest when maximum aggregates size was 19 mm. However, when the w/b ratio was low (w/b=0.30), there was a tendency that the highest cracking strain was obtained at smaller maximum aggregates sizes. Maximum aggregates size of 25 mm resulted in a small cracking strain in almost all tested mixtures. This result was consistent with the result of a previous study[17] which stated that, the cracking strain of low w/b ratio concrete decreased with the increasing of aggregates size. The reduction of cracking strain in large aggregates size was believed to be because of the lower surface



(a) Effect of maximum size of aggregate



(b) Effect of sand content

Fig 8. Effect of aggregate on cracking strain.

area and then lower bond between paste and the large size coarse aggregates.

Figure 8b shows that at early age, mixtures with a higher s/a ratio (s/a=0.44) showed slightly higher cracking strain than mixtures with a lower s/a ratio (s/a=0.36), but at 28 days, the cracking strains were about the same

Effect of Moisture Condition

Test results in Figure 9 to Figure 11 show that the flexural strength, the splitting tensile strength and the cracking strain of the oven-dried specimens and those of the wet specimens were different. It was noted here that the wet and oven-dried specimens were used only to demonstrate the effect of extreme cases of moisture condition. There was still no intension to study the effect of moisture content or moisture distribution in this study. The differences between the properties of oven-dried and wet specimens varied with types of mineral admixture. Kanna et al[20] and Haque[21] reported that, the strength and microstructure of concrete were affected by drying, especially if they contained mineral admixtures such as fly ash or slag. Drying coarsened the pore structure, lowered the Young's modulus but increased the fracture toughness. Figure 9 shows that the flexural strength and splitting tensile strength of oven-dried specimens were smaller than those of the wet specimens, and all mineral admixtures displayed the same tendency. The tensile strength reduced due to microcrack formation and severe stresses at the ITZ (leading to weakness of ITZ) when drying shrinkage occurred in concrete[20,22,23]. Yan and Lin[13] found that stress waves running across the voids and microcracks in concrete led to a considerable increase in stress in that region, while voids filled up with free water would reduce the damage.

Visual examination of the fractured surfaces of the tested concrete beams found that in the case of oven-dried specimens, all cracks passed through paste, and interface between paste and coarse aggregates. This led to a rough surface as shown in Figure 10a. This was explained by the weakness of the aggregates-paste interface due to microcracking and shrinkage stress intensity[22]. For wet specimens, the crack cuts through paste and coarse aggregates as shown in Figure 10b. This led to more flattened fracture surface and failure would take place at a higher stress level than those occurred in dry specimens. This was due to the fact that the presence of coarse aggregates requires lager force to break them and resulted in a higher stress level to bring them to failure.

Contrary to the flexural and splitting strength, Figure 11 shows that cracking strain of the oven-dried specimens was higher than that of the wet specimens. Test results in Table 3 showed the ratio of some mechanical properties of the oven-dried specimens to those of the wet specimens. Energy absorption capacity was defined as the area under the stress-strain curve up to the fracture stress. Test results showed that the energy absorption capacity was affected by the existence of moisture especially in the high w/b ratio concrete. When considering the ratio of energy absorption capacity of the oven-dried specimens to those of the wet specimens, it can be seen that the oven-dried specimens had higher energy absorption capacity than

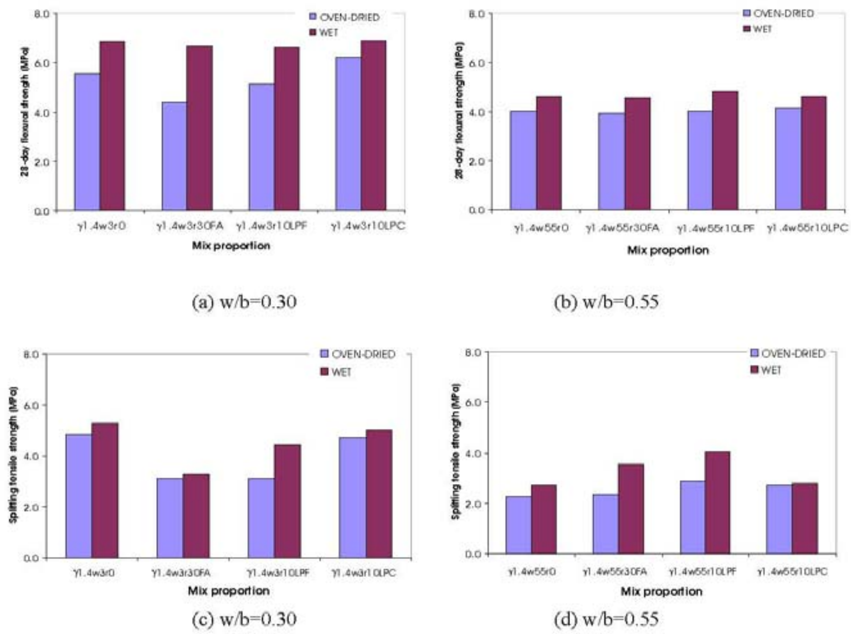
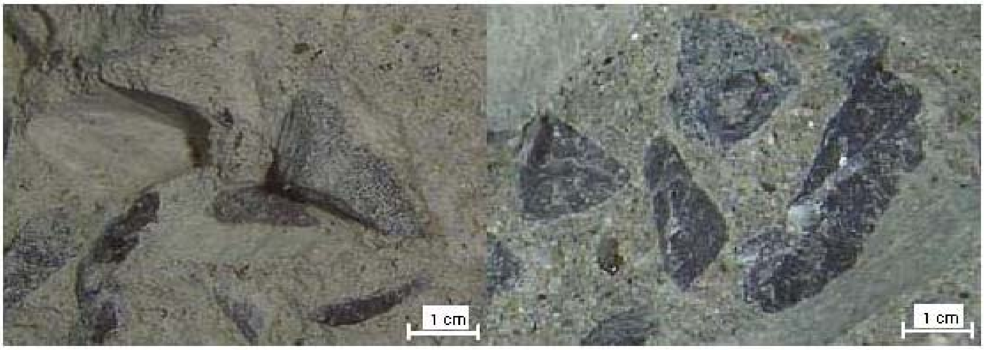


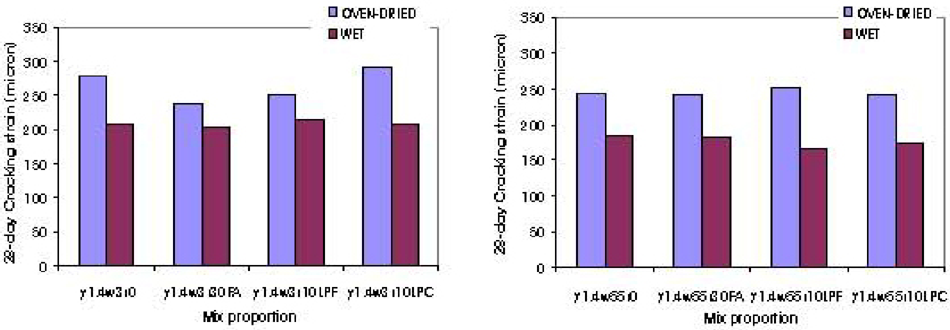
Fig 9. (a, b) Comparison of flexural strength between oven-dried and wet specimen. (c, d) Comparison of splitting tensile strength between oven-dried and wet specimens.

the wet specimens. In general, for concrete which has a high paste strength, the crack will cut through coarse aggregates. But when concrete was dry, microcracks can develop at aggregates-paste interface. These microcracks start to extend owing to stress concentration at crack tips. Then, some microcracks nearby the aggregates surfaces start to bridge in form of paste cracks, meanwhile, other bond cracks continue to grow slowly by seeking the path of least resistance along aggregates-paste interface, causing the strain to increase with no increase of stress[13]. This led to a rough fracture surface. In this condition, the flexural strength decreases, whereas the energy absorption capacity and the cracking strain increase. It was anticipated that if other mixture parameters and strength properties were the same, the cracking strain would be higher when the crack surface was rougher. However, it should be noted here that the oven-dried condition was not a real situation in practice. In actual environment, concrete was not completely dried. The differences between air-dried and wet concrete were not expected to be as great as shown here.



(a) Oven-dried specimen (b) Wet specimen

Fig 10. Photos of fractured surfaces affect by moisture condition.



(a) w/b=0.30 (b) w/b=0.55

Fig 11. Comparison of cracking strain between oven-dried and wet specimens.

Table 3. Comparative properties between the oven-dried and wet specimens.

No.	Mix proportion	Ratio of properties of oven-dried specimens to those of wet specimens		
		Cracking strain	Flexural strength	Energy absorption
1	γ1.4w3r0	1.33	0.80	0.96
2	γ1.4w3r30FA	1.16	0.65	0.92
3	γ1.4w3r10LPF	1.16	0.77	0.99
4	γ1.4w3r10LPC	1.40	0.91	1.22
5	γ1.4w55r0	1.33	0.87	1.15
6	γ1.4w55r30FA	1.33	0.86	1.17
7	γ1.4w55r10LPF	1.52	0.84	1.31
8	γ1.4w55r10LPC	1.40	0.89	1.24

Conclusions

Based on the test results in this paper, the following conclusions can be drawn.

1. Considering effect of age, cracking strain of concrete increases with age due to increase of strength. At early age, strength of paste was low so the crack propagates through the paste along the coarse aggregates-paste interface and the cracking strain increases with the strength of paste. When the strength of paste became higher, the crack cut through aggregates particles. The strength of paste and the quality of coarse aggregates-paste interface play an important role on the cracking strain of concrete.

2. The cracking strain of concrete varied with mix proportions and mineral admixtures. The cracking strain decreased with the increases of w/b ratio, replacement ratio of fly ash and limestone powder. The cracking strain increases with the increase of replacement ratio of slag (up to 50%). When the slag content was 70%, the cracking strain decreased especially at a high w/b ratio. When compared at the same 28-day compressive strength, the cracking strain of the fly ash concrete and the coarse-grain limestone powder concrete were about the same as that of the cement-only concrete. The fine-grain limestone powder concrete had a lower cracking strain than cement-only concrete, whereas the cracking strain of the slag concrete was higher. The cracking strain did not vary significantly with the type of cement (Types I, III and V).

3. The cracking strain of the high w/b ratio concrete (w/b=0.55) was the highest when maximum aggregates size was 19 mm. However, when the w/b ratio was low (w/b=0.30), there was a tendency that the highest cracking strain was obtained at smaller maximum aggregates sizes. At early age, the higher sand content (s/a=0.44) showed a slightly higher cracking strain than the lower sand content (s/a=0.36), but the cracking strain of both sand contents were about the same at 28 days.

4. The cracking strain, flexural strength, and splitting tensile strength of concrete were affected by the existence of moisture. When the concrete was oven-dried, the cracking strain increased due to the increase of energy required to make the crack grow. The flexural strength and splitting tensile strength decrease due to the microcracking and stress concentration in the aggregates-paste interface zone caused by drying shrinkage when the concrete was oven-dried.

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