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DEVELOPMENT OF HIGH MODULUS CONCRETE FOR TALL BUILDINGS

RESEARCH SUMMARY

Construction Industry Council

Development of High Modulus Concrete for Tall Buildings

Research Summary

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FOREWORD

Hong Kong is an international financial centre, with over 112 buildings that stand taller than 180 meters in the limited usable land with the first ranking in the world in both skyscraper and high-rise count. For tall buildings, its structural design is usually controlled by lateral deflection. To reduce the deflection, enhancing the stiffness of concrete is much more efficient than increasing the cross-section area of structural members. Hence, development of high modulus concrete may bring great flexibility to structural engineers.

The research work presented in this report was funded by the Construction Industry Council (CIC) Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. The CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, the CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

This project developed high modulus concrete through a suitable formulation of concrete mixture, as well as high range water reducing agent. The research results are quite encouraging. The stiffness enhancement is almost 20% compared with the same strength concrete level in the code of practice and lead to construction cost saving.

The research work described in the report was carried out by a research team led by Professor Zongjin LI from the Hong Kong University of Science and Technology. This project cannot succeed without the dedicated effort of Professor LI and the research team, and their contributions are gratefully acknowledged.

Ir Albert CHENG
Executive Director of Construction Industry Council

PREFACE

Construction of tall buildings becomes an unstoppable trend all over the world in recent decades. Concrete is the main construction material for these skyscrapers. When designing tall buildings with conventional concrete, large cross-section area for beams and columns has to be adopted due to the need of structural deformation control. However, there is no doubt that enhancing the modulus of concrete itself is much more efficient than increasing the cross-section area of structural members when the stiffness of a structural member needs to be improved. Hence, there is an urgent need to develop a concrete with high modulus of elasticity (high modulus concrete).

The Construction Industry Council in Hong Kong has noticed the problem, spotted the significance of concrete technology and opted to sponsor a research project on development and application of high modulus concrete which was jointly proposed by Gammon Construction Ltd. and The Hong Kong University of Science and Technology (HKUST) in 2013. The objectives of this research included: (1) to optimize mix proportions for high modulus concrete, (2) to characterize the properties of high modulus concrete, (3) to apply the high modulus concrete in producing structural members, and (4) to promote the high modulus concrete developed in this study to local construction industry.

Upon completion of the project, a novel high modulus concrete has been successfully developed by Gammon and HKUST. Its modulus of elasticity is miraculously 20% higher than normal concrete with the same strength level in the code of practice. High modulus concrete has demonstrated a very good workability, excellent mechanical property, outstanding dimension stability and durability. By using this concrete in tall buildings, 15-20% materials can be saved and up to 2-5% more useable space can be achieved. It provides a new option for construction of tall buildings and also gives a practical manual to produce such high modulus concrete. The trial tests conducted by Gammon and HKUST implied that it is ready for application at industry scale. CIC is also willing to support a pioneer construction project with high modulus concrete to benefit the society in the sense of sustainability and sustainable built environment. It is no doubt that high modulus concrete will lead to an unprecedented revolution in construction industry.

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EXECUTIVE SUMMARY

A new type of concrete, which contains volcanic aggregate and well-graded river sand, having both high strength and high modulus of elasticity has been developed for tall buildings, and its properties were characterized. The structural deformation of high-rise buildings can be substantially reduced by using this type of concrete.

Uniaxial compression tests, static elastic modulus tests were conducted to measure the mechanical properties of concrete specimens with different types of coarse aggregate, fine aggregate, different proportions of sand/coarse aggregate ratio and etc. The microstructure of interfacial transition zone between cement paste and aggregate was investigated by scanning electron microscope. The experimental results showed that concrete with volcanic rock as coarse aggregate and river sand as fine aggregate had higher stiffness than that with granite rock and crushed stone fines. Types of coarse and fine aggregate had significant effects on modulus of elasticity but had limited effects on compressive strength. Sand ratio around 43% and silica fume content about 10% were found suitable for making high modulus concrete. Water to cement ratio was the key issue in determining the concrete stiffness, and it should be minimized so that the lowest porosity and highest stiffness of cement paste can be achieved. Meanwhile, well-graded size distribution of river sand was better than uniform grading when developing high modulus concrete, and the aggregate to cement ratio cannot be too large because there must be adequate cement matrix surrounding aggregates. Mineral admixtures such as metakaolin and nano-silica led to higher modulus of elasticity of concrete, but the water/cement ratio had to sacrifice. At last, ultrasonic mixing technique was used for making high modulus concrete, and it was verified to be helpful for concrete stiffness. So far, a particular concrete with the compressive strength of 146 MPa and modulus of elasticity of 53.5 GPa was developed for tall buildings, which is much stiffer than normal concrete in the code of practice.

The majority of the factors influencing the modulus of elasticity of concrete have been studied experimentally and systematically. After that, four concrete mixtures including C45, C80, high modulus and ultra-high modulus concrete were tested for shrinkage and creep properties of concrete. The test results indicated that high modulus concrete had much smaller drying shrinkage value although its autogenous shrinkage was a little larger than normal concrete. Therefore, the total shrinkage of high modulus concrete was still smaller than that of normal concrete. Meanwhile, a constant load of 40 kN was applied on concrete cylinders to study the difference of creep properties among different types of concrete. High modulus concrete also showed better creep performance than normal concrete.

In the end, high stiffness concrete was applied in producing structural members, and the different performances among high modulus concrete, C80 and C45 were compared. The load capacity of reinforced ultra-high modulus concrete beam was approximately 30% higher than that of C45 concrete beam. At actual service stress level, the mid-span deflection of ultra-high modulus concrete beam was only roughly 48% of normal concrete. This deformation reduction verified the benefits of using high stiffness concrete in construction of tall buildings.

CONTENTS

1 INTRODUCTION

1.1 Background

Hong Kong is an international financial centre, with over 112 buildings that stand taller than 180 meters in the limited usable land. Hong Kong ranks the first in the world in both skyscraper and high-rise count, with at least 52 completed skyscrapers over the height of 200 m, 272 skyscrapers over 150 m as well as more than 7,687 high-rise buildings.

Concrete is the most widely used construction material nowadays, which literally forms the basis of our modern society. Especially for those tall buildings, concrete is becoming more popular. It is reported that the change in structural material has been very significant over the past few decades. All-steel buildings have dropped from 90% as recently as 1970, to 23% now in favor of concrete or composite structure. The main reason for the trend towards concrete/composite structure in tall buildings is that concrete has many advantages including ability to cast, economical, durable, fire resistant and energy efficient.

From the structural engineer’s point of view, a tall building is affected by lateral loading due to wind or earthquake actions to an extent that they play an important role in the structural design. The lateral drift of a tall building with n stories is proportional to n^4, which means that the emphasis of tall building analysis and design should be placed on the structural behaviour of the systems under lateral loading. Hence, adequate stiffness of structural members is necessary to prevent high level of lateral deformation including inter-story drift and top drift. Stiffness and drift limitations are usually becoming critical design criteria compared with strength and stability. There is no doubt that enhancing the stiffness of concrete is much more efficient than increasing the cross-section area of structural members if engineers need to control the deflection of a tall building. The purpose of construction of tall buildings is to obtain as much floorage as possible in limited land. So, development of high modulus concrete can also bring huge economic benefit. From the perspective of material mechanics, higher modulus means deforming less under the same loading or resisting larger force with the same deformation. Development of high modulus concrete may bring great confidence to structural engineers when they conduct structural design of tall buildings.

Concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard material matrix (the cement or binder) that fills the space between the aggregate particles and glues them together. Therefore, it is probable to develop a type of concrete with high modulus of elasticity by adjusting the components inside the concrete or the proportions among them. In this study, a suitable formulation of concrete mixture that has high compressive strength and high modulus of elasticity is developed by using suitable size and grading of the aggregates, as well as high range water reducing agent. Concrete mixes with different water to cement ratios, different types of coarse aggregates, different types of fine aggregate, and various coarse to fine aggregate ratios are cast. The key issues to improve the stiffness of concrete are to reduce or eliminate the interface zone, to improve aggregate packing, and improve the modulus of hardened cement paste. To reach the goals, different supplementary cementitious materials such as silica fume and metakaolin can be used. Water/binder ratio needs to be minimized and concrete mix ratio should be optimized. Porosity of concrete will be reduced accordingly if the elastic modulus increases. Thus, concrete with high modulus of elasticity may have better durability. In addition, high modulus concrete may generate smaller shrinkage and creep problems due to larger restraining effect of stiffer aggregates.

1.2 Research Aim, Objectives, and Deliverables

This research project has three objectives:

i. Optimize concrete mix for high modulus concrete

ii. Characterize the properties of the high modulus concrete developed in (i)

iii. Apply the high modulus concrete in producing structural members

The first stage was so significant that the latter two steps cannot proceed if the first one was not finished. Once the high modulus concrete was developed, its properties could be characterized and it could be utilized in producing structural members. Some comparison work could be done to verify the advantages of using high modulus concrete in construction of tall buildings.

2 METHODOLOGY AND MATERIALS

2.1 Raw Materials

As this research topic is based on practical use of concrete for tall buildings, most of the raw materials used in the experiments are delivered from normal construction site. During the whole research process, raw materials were kept with the same composition and quality to make sure that test results are comparable.

For binders, ordinary Portland cement (OPC), pulverized fly ash (PFA), condensed silica fume (CSF) were used for mixing concrete. Meanwhile, some additional mineral admixtures such as metakaolin (MK) and nano-silica (nano-SiO_2) were added into the concrete to improve its properties. Cement used in this study was Asano 52.5 type. PFA, which is the most extensively used mineral admixture, is the inorganic, noncombustible residue of powered coal after burning in power plant. Fly ash for this project was delivered from CLP and its XRF test result is listed in Table 2.1. Condensed silica fume was also used in this study because it was reported that silica fume is beneficial to mechanical properties and durability of high strength concrete. It is a by-product of the manufacture of silicon and ferrosilicon alloys from high-purity quartz and coal in a submerged-arc electric furnace. It has a SiO_2 content between 85 to 96 percent of total weight and the average particle size is roughly 130 nm.

Table 2.1 Main chemical compositions of fly ash (wt. %)

Element	Weight %
SiO_2	55.25
Al_2O_3	27.90
Fe_2O_3	7.45
CaO	4.63

With the deepening of this research, some additional mineral admixtures such as metakaolin and nano-silica were used. Metakaolin is one of the recently developed supplementary cementing materials for high-performance concrete. It is produced by calcining purified kaolinite clay in a specific temperature range (650 to 800 ^{o}C) to drive off the chemically bound water in the interstices of kaolin and destroy the crystalline structure, which effectively converts the material to the MK phase, an amorphous aluminosilicate. Metakaolin used in this study has the particle size which is smaller than cement but larger than silica fume. The properties of metakaolin used are listed in Table 2.2. Meanwhile, nano particles were also considered to be added in the concrete mixture. Nano-silica is a kind of admixture which has relatively small particle size and high percentage of SiO_2 content. The SiO_2 content is greater than 99.8% and its average particle size is only 12 nm. The surface area of nano-silica is approximately 200m^2/g, which is quite large; therefore, its bulk density is only 50 g/L.

Table 2.2 Main chemical compositions and other properties of metakaolin

Element	Weight %
SiO_2	51.76
Al_2O_3	42.53
Fe_2O_3	0.43
TiO_2	1.74
Color	Cream white
Particle structure	Amorphous
Average particle size	1.4 μm
Specific gravity	2.2

Aggregate plays an important role in concrete mixture since it occupies about three-fourths of the concrete volume. The aggregate size and its grading have great influences on the properties of both fresh and hardened concrete. In this study, two types of coarse aggregate, granite rock and volcanic rock (Figure 2.1), were used, and each of them had two grading sizes (10 mm and 20 mm in diameter). Granite rock has light grey/yellow color while volcanic rock has dark grey/black color. It is reported that granite is a coarse grained plutonic rock composed of orthoclase, plagioclase and quartz while volcanic rock is formed from volcanic ash. Volcanic rock has higher strength and hardness than granite rock although granite is the most widely used coarse aggregate for concrete.

Figure 2.1 Two types of coarse aggregate with 10/20 mm particle size

For fine aggregate, due to government's environmental requirements, river sand is not advocated to be used for constructions. Crushed rock fines are widely used nowadays. In this study, crushed granite/volcanic rock fines as well as river sand (Figure 2.2) were used for making high modulus concrete. During tests, sieve analysis of fine aggregate was conducted to achieve the most suitable size distribution of sand for high stiffness concrete. The detailed test result is shown in Chapter 3.

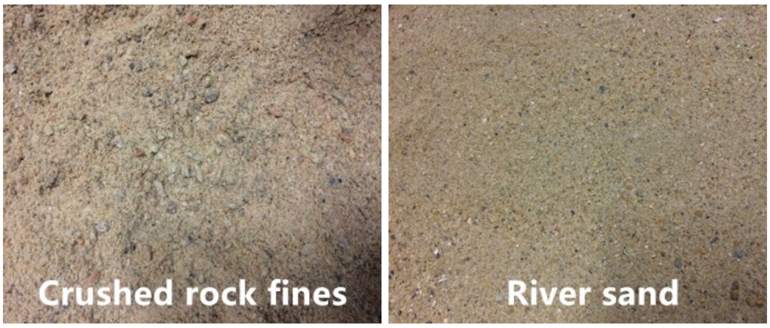


Figure 2.2 Two types of fine aggregate: crushed rock fines and river sand

Since lower water/cement ratio is the key approach to develop high modulus concrete, large amount of superplasticizer is needed to improve the workability of fresh concrete. Glenium SP8S produced by BASF Co. Ltd is a new generation superplasticizer for concrete. It contains polycarboxylate ether polymers and is specially formulated to give exceptionally high water reduction and significantly reduced slump loss. Glenium SP8S is one of the most popular and effective superplasticizers in the world. In addition, normal tap water was used for mixing with binders and aggregates.

2.2 Compressive Strength and Modulus of Elasticity Tests

For each mix proportion, twelve 100 x 100 x 100 mm cubic specimens and twelve Φ100 x 200 mm cylindrical specimens were cast. Cubic specimens were cast for cubic compressive strength test while cylindrical specimens were for the measurement of cylindrical compressive strength and modulus of elasticity. For mixing procedures, traditionally, after weighing all raw materials and moistening the mixer, gravels and sand are added first for dry mix for one or two minutes. After that, a small quantity of water and required binders are added and mixed for a while. Finally, remaining water is added and mixed for another two minutes. However, for mixing high modulus concrete, there is less water, more binders and large quantities of superplasticizer. Aggregate must be uniformly distributed in the cement matrix to achieve high quality. Therefore, a unique mixing procedure is applied in this study. All binders including cement, fly ash and etc. are added to the mixer first as well as water and superplasticizer. After mixing for about 2 minutes, cement slurry is obtained. Coarse and fine aggregate are then added and mixed for another several minutes until the fresh concrete is formed. The main advantage of this new mixing approach is that all binders can be evenly distributed in the water so that the mechanical properties of the concrete can be improved.

Figure 2.3 Specimen casting (12 cubes and 12 cylinders for each mix)

After mixing, slump test was conducted to measure the workability of fresh concrete. Since the concrete developed in this study is especially designed for construction of tall buildings, good workability should be guaranteed for concrete pumping. Thus, 100 mm slump is the lowest acceptable value. Freshly mixed concrete are then placed into the moulds. Vibration rod was used to consolidate the fresh concrete to remove the air bubbles. The specimens were demoulded after 24 hours and then placed in curing room at 23°C and 100% relative humidity until testing.

100-mm cubic compressive strength test is the most common test carried out on concrete. The development of cubic compressive strength was measured with unit test machine at the age of 7, 14, 28, and 56 days (Figure 2.4). The loading rate was kept at 3 kN/s (i.e. 18 MPa/min) constantly, and three 100 x 100 x 100 mm cubes for each formula were tested at each age.

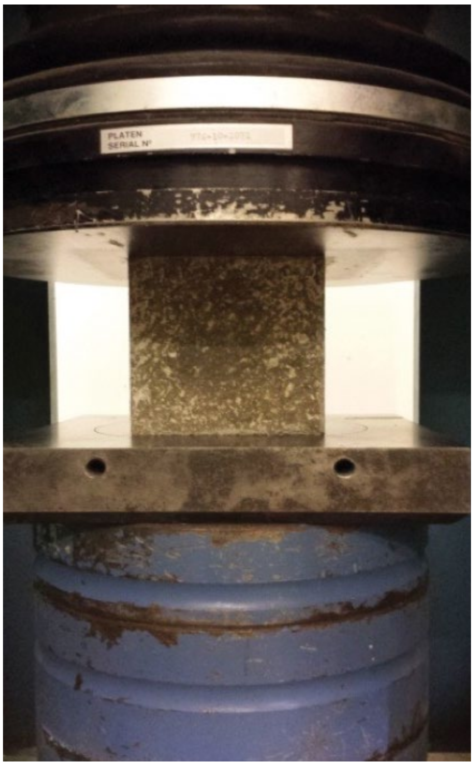


Figure 2.4 Experimental setup for cubic compressive strength test

As introduced in Chapter 1, the stress-strain curve for concrete is not linear. However, to calculate the expected deflection of structural members, it is necessary that some estimation of the modulus of elasticity, E, to be obtained. Although it is possible to define E in a variety of ways for a material with a nonlinear stress-strain curve, the most common way for concrete is to measure the chord modulus of elasticity following the method outlined in ASTM C469. The experimental setup of modulus test is shown in Figure 2.5. The cylindrical specimen should be capped before modulus test to make sure the top and bottom surfaces are smooth and parallel with each other. Two longitudinal extensometers are installed to measure the elongation of the specimen while a circumferential extensometer is installed in the middle of the cylinder to record the circumferential strain. Three cycles of pre-load and unload are applied to eliminate the abnormal deformation of the specimen. It is then loaded slowly (at a stress rate of 0.25 MPa/s) in compression, and a stress-strain curve can be obtained. The chord modulus of elasticity is calculated using the expression

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050}$$

where S_2 is the stress corresponding to 40% of the ultimate load; S_1 is the stress corresponding to a longitudinal strain, ε_1, of 50 x 10^{-6}; and ε_2 the longitudinal strain produced by stress S_2.

Figure 2.5 Experimental setup for modulus of elasticity test (static)

Initially, 4 different concrete mix proportions (Table 2.3) were provided by a local contractor. These mix designs have been applied in many construction projects so that they are mature and reliable. Two of them have the compressive strength level of 45 MPa and the other two are 60 MPa and 80 MPa, respectively. One 45 MPa concrete mix has the slump value of 100 mm, while the others have the slump of 200 mm. With the strength going up, the water/cement ratios of these mix proportions decrease. Larger dosage of superplasticizer is required for lower w/c ratio mix to enhance the workability of fresh concrete. The detailed mix designs are shown in the table below.

Table 2.3 Initial mix designs for high modulus concrete

Strength grade of concrete	Category class of concrete	OPC + PFA + CSF	OPC	PFA	CSF	20mm	10mm	S/F	Water	KFDN-100	KFDN-SP8G	Glenium SP8S	*w/c*	*A/c*
MPa		kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	L/m^3	L/m^3		
45/20D	100 mm slump (PFA, S/F)	460	345	115	0	515	415	720	200	2.99	2.0 ± 1.0	0	0.43	3.59
45/20D	200 mm slump (PFA, S/F)	430	320	110	0	520	420	820	165	0	0	6.0 ± 2.0	0.38	4.09
60/20D	200 mm slump (PFA, S/F)	505	380	125	0	530	430	720	165	0	0	6.0 ± 2.0	0.33	3.33
80/20D	200 mm slump (PFA, CSF, S/F)	535	398	105	32	530	430	740	150	0	0	12.0 ± 2.0	0.28	3.18

It should be noted that condensed silica fume is only utilized for the high-strength concrete with a compressive strength of 80 MPa. 10 mm and 20 mm coarse aggregate used in these initial mix designs is granite rock and the fine aggregate is crushed rock fines. In the concrete mix of C45 (100 mm slump), KFDN-100 is a kind of retarder and KFDN-SP8G is a kind of water reducer. Glenium SP8S is a kind of strong superplasticizer produced by BASF. Concrete specimens were prepared according to these mix designs and the general test results of initial mix design are shown in Chapter 3. Meanwhile, the whole process of optimization of mix proportions for high modulus concrete along with experimental results are introduced in details in next chapter.

2.3 Shrinkage and Creep Test

The materials used in shrinkage and creep test were the same with previous experiments. Four different concrete mixtures with various compressive strength and modulus of elasticity were cast for this dimensional stability investigation. Details of the concrete mix proportions are shown in Table 2.4, while the 28-day compressive strength and modulus of elasticity of concrete are given in Table 2.5. Cylindrical concrete specimens with the diameter of 100 mm and the height of 200 mm were cast for shrinkage and creep test. Two types of concrete shrinkage (total shrinkage and autogenous shrinkage) were measured respectively from 24 hours after casting. For the measurement of autogenous shrinkage, the specimens were demoulded and sealed with aluminium waterproofing tape. This sealing approach was verified to be quite effective since the specimens showed very minimal weight loss which could be neglected. Shrinkage was measured using CT-171M Demac strain gauge with the initial gauge length of 100±1.5 mm. The position of the measurement was located at the middle 100-mm part of the cylinders. The measurement of total shrinkage was conducted on the unsealed specimens with the same testing procedures as the measurement of autogenous shrinkage. All specimens were stored in a controlled environment of 23±2ºC and 55±5% relative humidity throughout the whole period of the experiment (Figure 2.6).

Table 2.4 Mix proportions for shrinkage and creep test

No.	OPC	PFA	20mm Gra.	10mm Gra.	S/F	Water	KFDN-100	KFDN-SP8G
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	L/m^3	L/m^3
C45	345	115	515	415	720	200	3	2
No.	OPC	PFA	CSF	20mm Gra.	10mm Gra.	S/F	Water	SP 8S
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	L/m^3
C80	398	105	32	530	430	740	150	12
No.	OPC	PFA	CSF	20mm Vol.	10mm Vol.	River Sand	Water	SP 8S
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	L/m^3
HEC	440	90	55	530	430	740	135	18
No.	OPC	PFA	CSF	20mm Vol.	10mm Vol.	River Sand	Water	SP 8S
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	L/m^3
UHEC	435	85	55	545	445	755	115	20

Table 2.5 Compressive strength and modulus of elasticity of concrete mixtures for shrinkage and creep test

Specimen	Compressive strength (MPa)	Modulus of elasticity (GPa)
C45	63.6	33.7
C80	102.0	39.5
HEC	116.3	47.3
UHEC	139.3	51.5

HEC: high stiffness concrete
UHEC: ultra-high stiffness concrete

Figure 2.6 Concrete specimens for autogenous and total shrinkage test

The creep test was conducted according to ASTM C512 using Φ100 x 200 cylinders. Figure 2.7 shows the setup for creep test. Four specimens were tested on a constant loading frame. To ensure a flat contact, sulphur compound capping was made at the ends of each cylinder. When test started, load was added to specimens by a hydraulic jack. Meantime, the spring (30 tons capacity) was compressed. After the load reached the specified values, the nuts were fastened to keep the load constant. The load value was checked twice a week and it was found that the frame could keep very stable loading. The load added to the specimen was 40 kN constantly, which equalled to 20% of the compressive strength of C45 concrete at ages of two days. The creep test started from 2 days after casting and the measurement approach was the same as shrinkage test. To ensure the reliability of the measurement, only one person was assigned to this job. Also, the Demac gauge was always kept in the dry room and exposed to same environment to reduce the temperature difference influence.

Figure 2.7 Experimental setup for creep test

2.4 Reinforced Concrete Beam Bending Test

Previously, the test specimens were limited in the material scale. However, the high modulus concrete is developed for real constructions. Therefore, the test specimens were then enlarged to structural scale. The application of high stiffness concrete in producing structural members were conducted as the last stage of this research project. Since column members are similar with the cylindrical specimens tested in the past experiments, beam members were designed for structural member test to study the applicability of high modulus concrete.

The overall dimensions of the rectangular reinforced concrete beams were the same for all test members, i.e., beam width *b* = 120 mm, beam height *h* = 220 mm, and beam length = 1800 mm. The span length for the beam was *l* = 1600 mm. The two steel bars in the tensile area were Y12 which has the yield strength of 500 MPa. R8 steel bars were utilized for compression area and stirrup, and its yield strength was 250 MPa. Three LVDTs (shown in Figure 2.8) were installed at the bottom of each beam to measure the beam deflection so that the structural deformation curvature can be obtained.

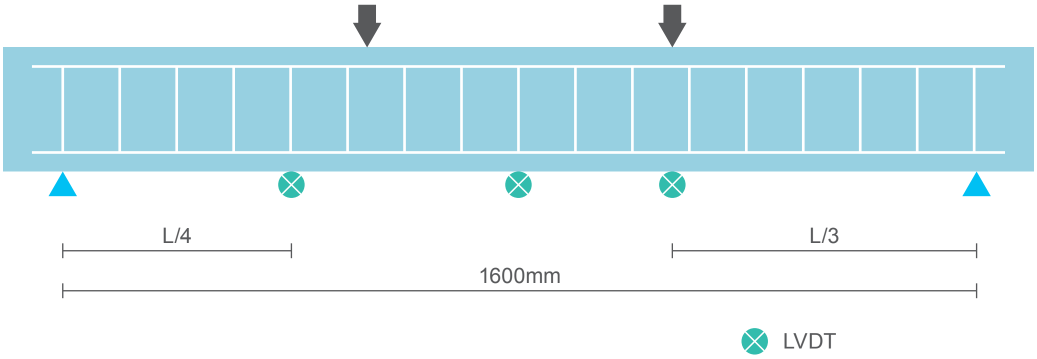


Figure 2.8 Schematic diagram for reinforced concrete beams

The concrete used for structural members were named as C45, C80, HEC (high stiffness concrete) and UHEC (ultra-high stiffness concrete), respectively. Steel fiber was also used for high stiffness concrete and C80 concrete to improve the toughness and ductility. The mix proportions and the mechanical properties of all four concrete mixtures were the same as those in shrinkage and creep test. The details of the related information are shown in Table 2.4 and Table 2.5. After designing the reinforced concrete beams and concrete mixtures, 8 concrete beams were cast and cured for 28 days until testing (Shown in Figure 2.9).

Figure 2.9 Concrete beams during casting (left) and after demoulding (right)

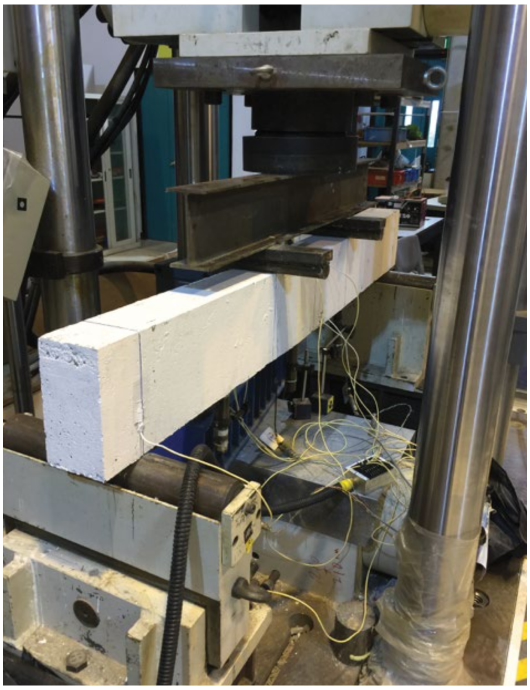


Figure 2.10 Experimental setup for reinforced concrete beam bending test

The test beams were loaded in four-point bending condition. The experimental setup is shown in Figure 2.10. The loading rate was kept constantly at 0.02 mm/s until the specimen failed (i.e. concrete in compression zone failed). The vertical deflection at the midpoint of the specimen was measured by LVDT. The measurement was automatically recorded and stored in the data-acquisition system.

3 RESULTS AND FINDINGS

3.1 Optimization of Concrete Mix for High Modulus Concrete

3.1.1 General test results

Cubic and cylindrical compressive strength and modulus of elasticity tests were conducted on the specimens with initial mix designs. The test results (see Table 3.1) indicate some general ideas about the development of concrete strength and stiffness. It can be seen that the 28-day strengths of all four groups meet the required strength levels. The compressive strength at 7 days is over 70% of the compressive strength at 28 days, indicating that the strength gains to a large extent at early age. For C80 high strength concrete, this ratio increases to more than 80% due to the pozzolanic reactivity of silica fume. This strength proportion is quite essential and important because for construction of tall buildings, as the formwork will be moved up to the upper story about three or four days after the placement of concrete. Meanwhile, at 7 days, the modulus of elasticity of concrete can reach over 90% of the 28-day modulus, indicating that concrete gains more stiffness than compressive strength at early age. Still, this 7-day/28-day modulus ratio of high-strength concrete is larger than that of normal-strength concrete.

Table 3.1 Compressive strength and modulus of elasticity of concrete with initial mix design

Mix No.	Strength grade / slump	Age (days)	$f_{c(cube)}$ (MPa)	$f_{c(cylinder)}$ (MPa)	E (GPa)
1	45 MPa 100 mm slump	7	48.8	38.1	30.37
		14	57.6	45.6	31.50
		28	63.6	52.3	33.69
		56	71.9	58.3	33.85
2	45 MPa 200 mm slump	7	61.2	50.4	33.15
		14	71.5	56.4	34.18
		28	77.6	64.7	36.06
		56	88.3	74.6	36.82
3	60 MPa 200 mm slump	7	70.3	57.7	35.08
		14	81.2	62.3	36.18
		28	88.7	72.2	38.01
		56	98.2	83.1	38.72
4	80 MPa 200 mm slump	7	85.9	72.0	37.21
		14	93.5	81.0	38.51
		28	102.0	82.4	39.51
		56	110.7	94.0	40.33

When doing concrete modulus of elasticity test, cylindrical specimen was used. Three cycles of load-unload with the magnitude of 40% of the ultimate strength was applied before compressing the specimen until failure. Therefore, a suitable automatic-control compression procedure was essential for the modulus test. Cubic compressive strength was used to estimate the cylindrical compressive strength so that a suitable procedure could be selected. The relationship between cylindrical compressive strength and the cubic compressive strength was approximately constant according to the test results of these four batches. A good linear relationship was obtained (Figure 3.1) and the conversion coefficient was 0.825. This ratio was used to predict the cylindrical compressive strength in the following study and it seemed conservative for ultra-high strength concrete. The following test results showed that for ultra-high strength concrete with the 100-mm cubic compressive over 120 MPa, this ratio became larger, which is even close to 0.95. Development of mix design of high modulus concrete was based on the C80 concrete mix. The modification of mix proportions was introduced and the factors influencing the modulus of elasticity of concrete were analysed in the following part.

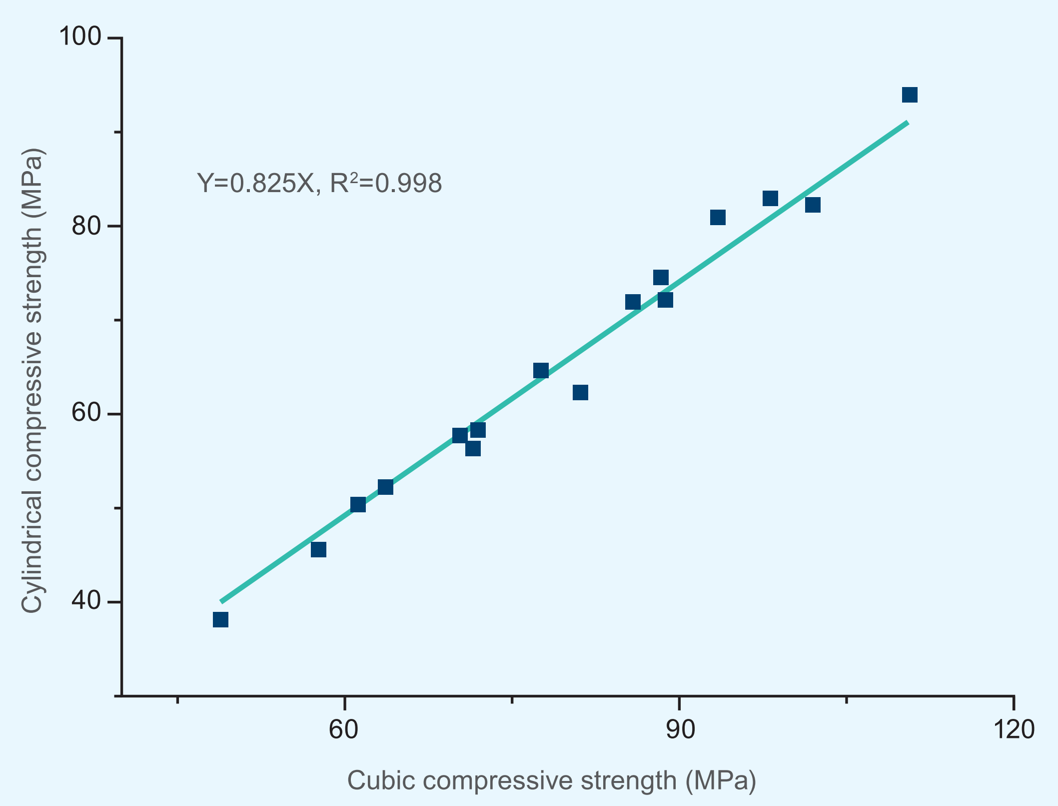


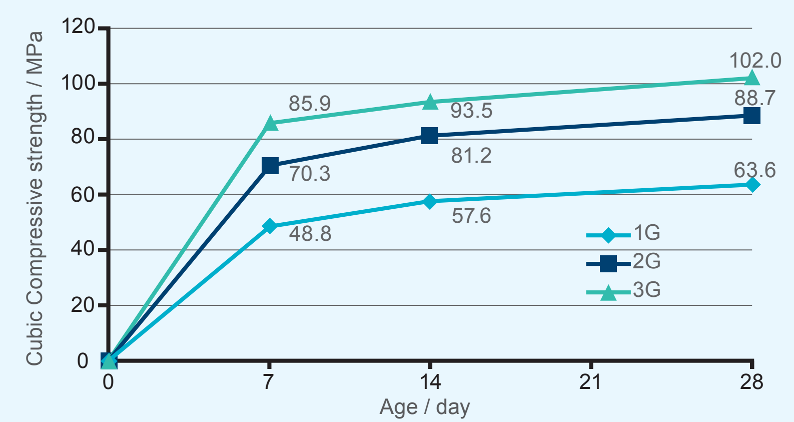
Figure 3.1 Relationship between cubic and cylindrical compressive strength

3.1.2 Factors influencing the modulus of elasticity of concrete

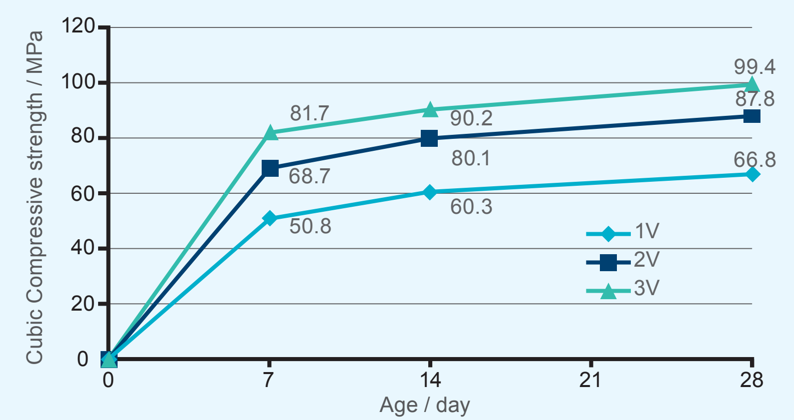
Volcanic and granite rock were used as coarse aggregate, and crushed rock fines and river sand were used as fine aggregate. The effects of two different coarse/fine aggregate ratios and two different fine aggregate grading were also studied. Different aggregate to binder ratios were tried to obtain the optimized value. Mineral admixtures such as metakaolin and nano-silica were added to the concrete mix, improving grading of binders and reducing porosity. Water/cement ratio was minimized from 0.28 to 0.20 by using large dosage of superplasticizer. Finally, an optimized concrete mix with both high strength and high stiffness is obtained, but there are still some contradictions to be resolved.

i. Two types of coarse aggregate

Three groups of concrete specimens with different strength levels were tested to measure the compressive strength and modulus of elasticity. For each group with the same strength level, the only difference of the components was the type of coarse aggregate. Granite rock and volcanic rock were used respectively. The shape and texture of granite rock and volcanic rock looked similar and the gravel sizes were also identical. The mix proportions were the same as C45 (100mm slump), C60 and C80 in Table 2.3.



Granite as Coarse Aggregate



Volcanic as Coarse Aggregate

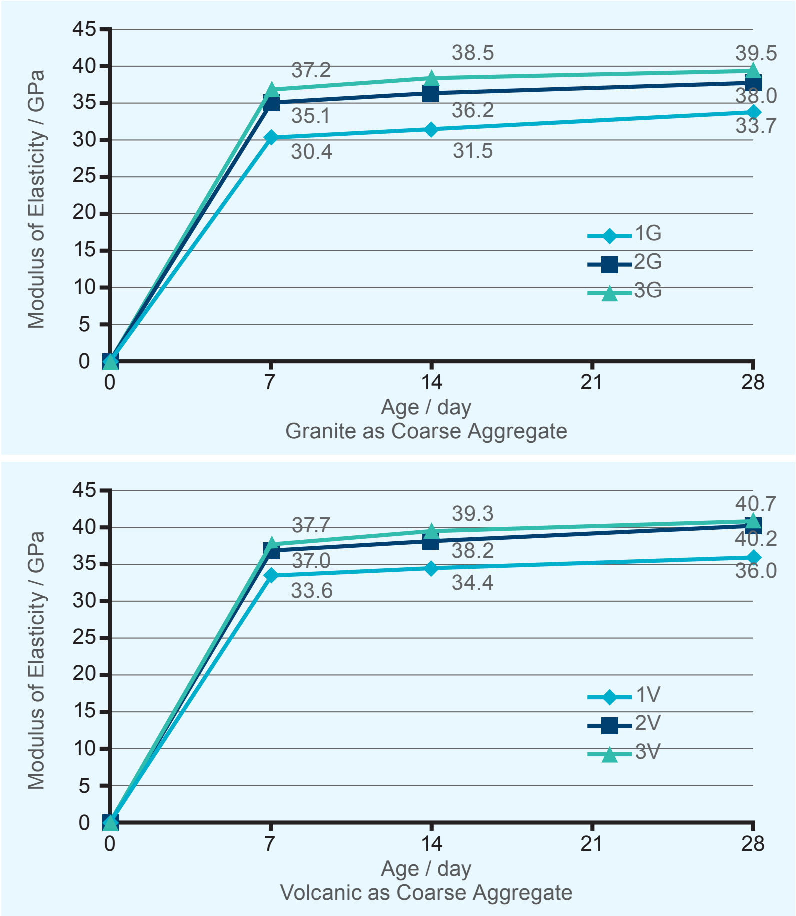


Figure 3.2 Compressive strength and modulus of elasticity of concrete with different strength levels containing different types of coarse aggregate

The compressive strength and modulus of elasticity of these specimens at different ages are shown in Figure 3.2. Group No. 1, 2 and 3 represent C45 (100 mm slump), C60 (200 mm slump) and C80 (200 mm slump), respectively. It can be seen from the figure that both the strength and stiffness increased dramatically during the first seven days. The strength can reach over 70% of the 28-day compressive strength and the stiffness can be over 90% of the 28-day modulus of elasticity in one week. This provides an effective method to predict the mechanical properties of concrete before 28-day tests. Besides, there was almost no difference between compressive strength of concrete with different coarse aggregate. However, when changing the coarse aggregate from granite to volcanic, the modulus of elasticity increased. These results indicated that the type of coarse aggregate has significant effect on the modulus of elasticity of concrete but limited influence on its compressive strength if the grading, shape and texture of the aggregate are similar. The reason for this phenomenon may be that the compressive strength of concrete specimen is determined by the weakest interface inside the concrete specimen. For high strength concrete, the weakest interface is the interfacial transition zone between aggregate and cement paste, rather than the aggregate itself. That is why the strength has little relationship with the type of coarse aggregate. However, the stiffness of concrete depends on the stiffness of each component. So, the higher stiffness of coarse aggregate will lead to higher modulus of elasticity of concrete.

ii. Sand ratio

Previous researchers reported that reducing sand ratio can improve the elastic modulus of concrete. However, such point of view only appears two times and has not been proved as a general case. To verify this theory, a 5% reduction of sand ratio from Group 1 (C45) and 2 (C60) concrete mixes was conducted. Coarse aggregate used in these specimens was volcanic rock, which contributed more to high modulus of concrete.

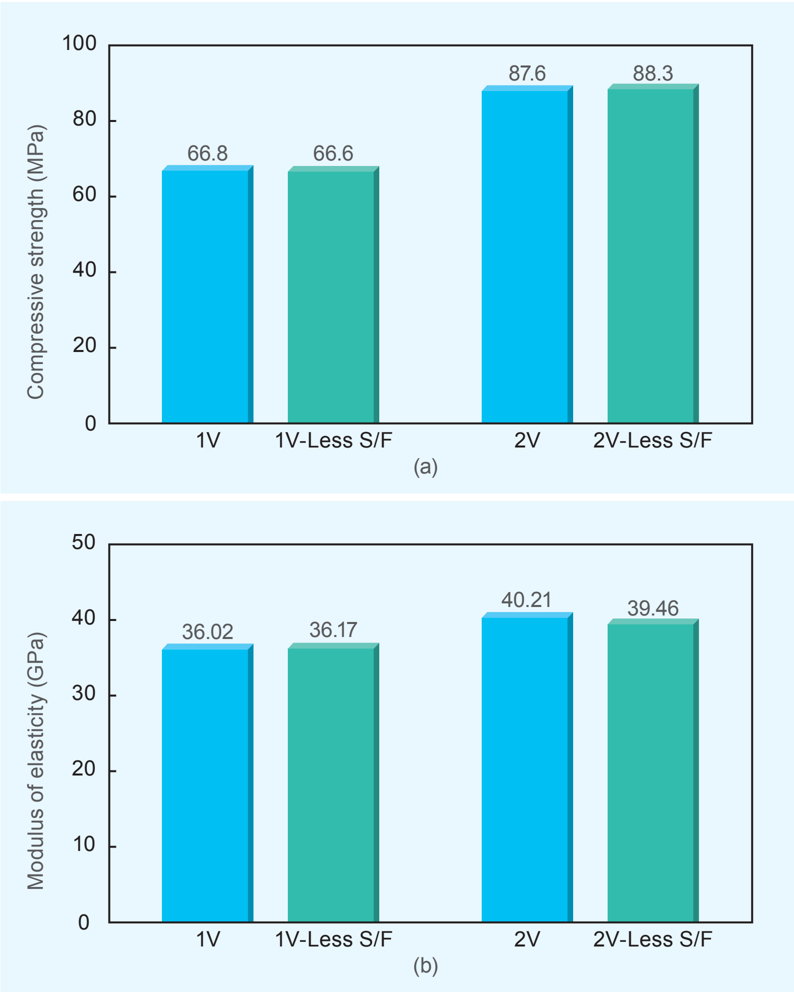


Figure 3.3 Compressive strength (a) and modulus of elasticity (b) of concrete with different fine aggregate ratios

The compressive strength and the modulus of elasticity of the specimens with different sand ratios are shown in Figure 3.3. The test results showed that a 5% reduction of sand ratio made the compressive strength go down slightly and it had no obvious influence on the elastic modulus of concrete, which meant that the sand ratios of original mixture proportions were suitable and applicable for making high modulus concrete. This was possibly because lower sand ratio made the grading of solid particles inside the concrete not continuous and the porosity increased. Meanwhile, too much coarse aggregate may cause segregation problem of fresh concrete, which may affect the mechanical properties of hardened concrete.

iii. Two types of fine aggregate

Since crushed rock fines (artificial sand) used for concrete mixing looked too pulverized to provide dense structure of concrete, river sand instead of stone fines was used as fine aggregates for high modulus concrete. For concrete mix, volcanic rock was used as coarse aggregate and the water/cement ratio was 0.28, which had the target compressive strength of 80 MPa. The detailed mix proportion is shown in Table 3.2. S/F represents crushed stone fines and RS stands for river sand.

Table 3.2 Mix proportions of concrete with different types of fine aggregate

Class of Concrete	OPC	PFA	CSF	Volcanic 20mm	Volcanic 10mm	S/F or RS	Water	SP8S	*w/c*
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	
3V (C80)	398	105	32	530	430	740	150	12.0 ± 2.0	0.28

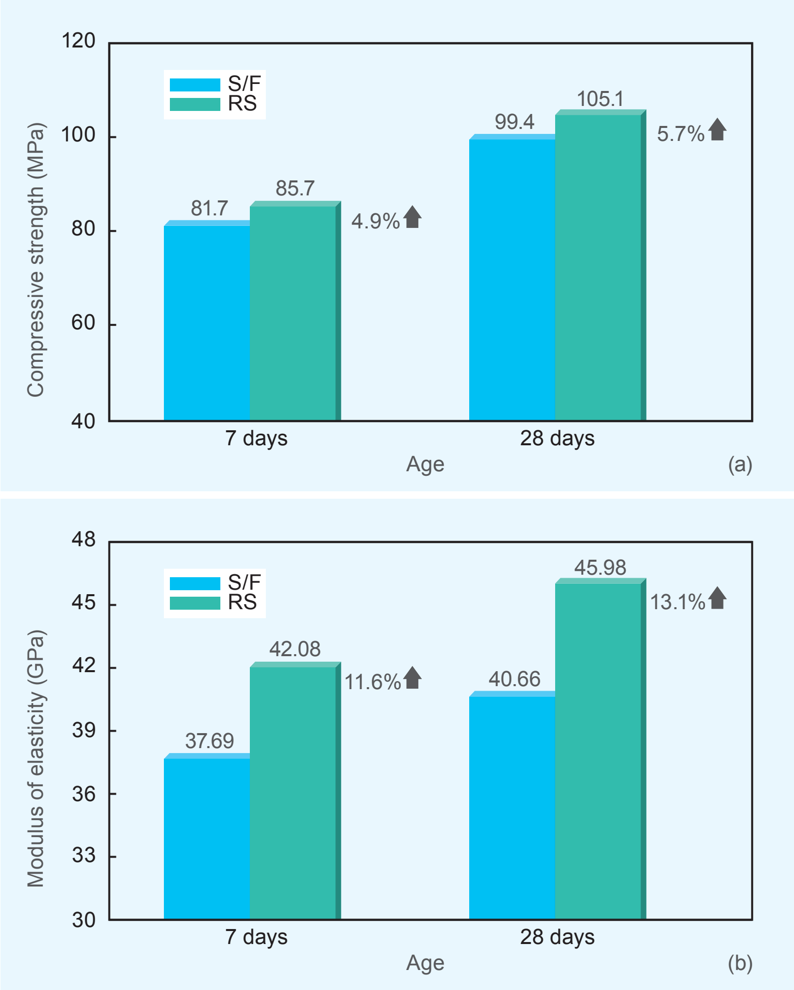


Figure 3.4 Compressive strength (a) and modulus of elasticity (b) of concrete with different types of fine aggregate (crushed stone fines / river sand)

The test results showed that when changing the fine aggregate from crushed stone fines to river sand, the compressive strength of concrete increased by approximately 5 percent. Meanwhile, the modulus of elasticity of concrete with river sand had much higher stiffness than that with rock fines. The increment was more than 13 percent, which meant that the replacement of fine aggregate had more effects on stiffness than on strength (Figure 3.4). It is obvious that the grading of river sand and its main component, silicon dioxide, is beneficial to concrete stiffness improvement. Stone fines is the product after crushing the raw rock stones so that its quality varies bag to bag and there is much dust mixed with rock fines. The shape and texture of the fine aggregate was also studied by using the optical microscopy. It was found that most of the aggregate particles of river sand were spherical, cubical and irregular, which are good for application in concrete because they can benefit the strength.

However, particles in crushed rock fines were flat, needle-shaped or prismatic, which are weak in load-carrying ability and easily broken. Besides, the smash process of stones may destroy the aggregate structure or induce some micro-cracks inside the particles, hence influences its loading capacity.

iv. Silica fume

Silica fume is a widely used cementitious material for high strength or high performance concrete due to its reaction with CH. The original substitution of silica fume from the cement is 6% in C80 mix. To verify the effect of silica fume on the high strength concrete, double amount of silica fume was also tried on the basis of C80 concrete mix.

During mixing, it was observed that larger amount of silica fume made fresh concrete more cohesive and the fluidity reduced. Concrete specimen with 12% condensed silica fume showed a slightly higher compressive strength and modulus of elasticity than that with 6% silica fume at 28 days. It verified that silica fume is an indispensable material for high modulus concrete but the replace percentage should be controlled. Therefore, around eight to ten percent silica fume of total binders is suitable and essential for making high modulus concrete.

v. Water to cement ratio

Water/cement ratio determines the porosity of the hardened cement paste at any stage of hydration. When the type and the volume fraction of aggregate are fixed, enhancing the stiffness of hardened cement paste is an effective approach to improve the stiffness of concrete. On the other hand, void itself inside the hardened concrete does not have any stiffness. Therefore, reducing water/cement ratio is helpful to increase the modulus of elasticity by reducing the porosity of concrete. The initial water/cement ratio of C80 concrete mix was 0.28 with small amount of superplasticizer. This ratio was then minimized to 0.23 and even 0.20 by adding large dosage of superplasticizer. The mix proportions are listed in Table 3.3. It should be pointed out that the water content inside the superplasticizer is not considered when calculating the water/cement ratio of concrete in the engineering practice. The coarse and fine aggregate used for these mix proportions were volcanic rock and river sand, which had been proved effective for improving concrete stiffness.

Table 3.3 Mix proportions of concrete with different water/cement ratios

Mix No.	OPC	PFA	CSF	Volcanic 20mm	Volcanic 10mm	River sand	Water	SP8S	*w/c*
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	
A	405	90	50	525	425	735	150	12.0	0.28
B	425	90	50	535	435	745	130	18.0	0.23
C	435	85	55	545	445	755	115	20.0	0.20

It can be seen from Figure 3.5 that when reducing water/cement ratio, the compressive strength and the modulus of elasticity increased dramatically. The concrete mix at *w/c* ratio of 0.20 had the highest compressive strength of almost 140 MPa and the highest elastic modulus of 51.5 GPa. Concrete mix with such mechanical properties can be regarded as ultra-high strength and high modulus concrete, which is beneficial to the construction of tall buildings.

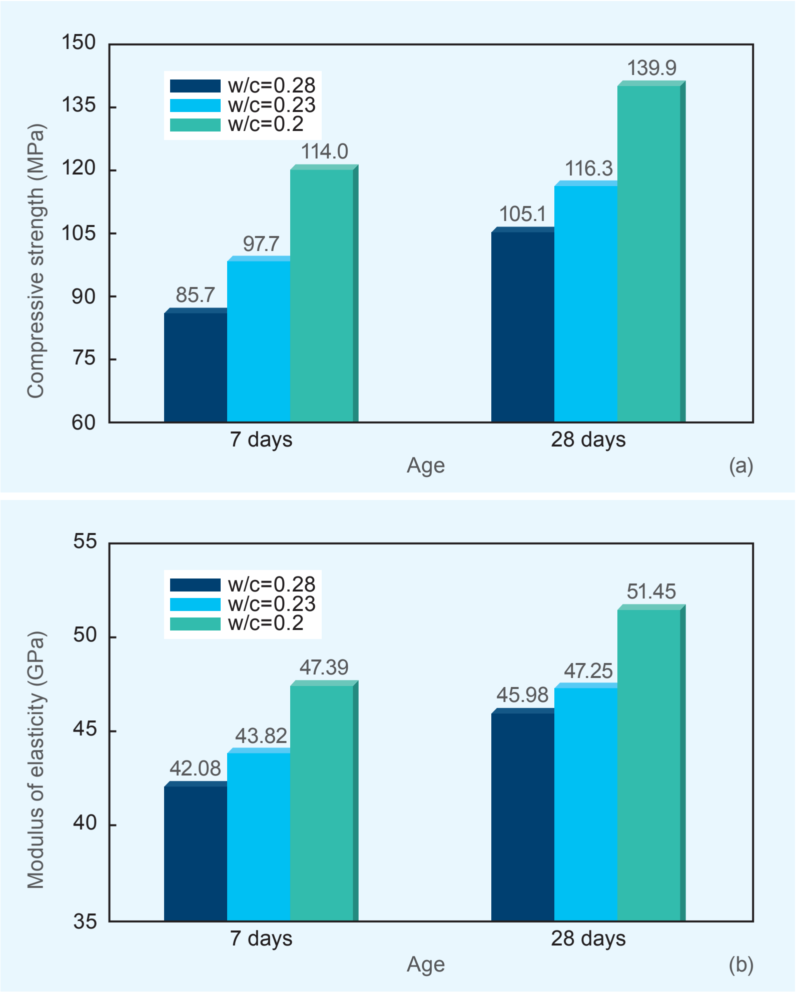


Figure 3.5 Compressive strength (a) and modulus of elasticity (b) of concrete with different water/cement ratios (0.28, 0.23 and 0.20)

vi. Grading of sand

The particle size distribution of aggregates is called grading. Combining coarse and fine aggregates to produce a desired grading is an important issue for making high modulus concrete. To obtain a grading curve for an aggregate, sieve analysis has to be conducted. In this study, the total aggregate in concrete mix proportions is divided into three categories: 20 mm coarse aggregate, 10 mm coarse aggregate, and fine aggregate. When the amount of two size coarse aggregate is determined, fine aggregate is the only part to be modified. Particle size distribution of fine aggregate not only affects the workability of fresh concrete, but also influences the strength and stiffness of hardened concrete. Sieve analysis was conducted for the normal river sand provided by material lab, and the results showed that the normal river sand mixed for high modulus concrete is close to uniform grading since almost half (48.1 wt.%) of the sand has the particle size between 0.300 mm and 0.600 mm. This uniform size distribution of fine aggregate is not the most suitable one for concrete mixture. Hence, another batch of concrete specimens with well-graded sand grading was prepared to study the influence of fine aggregate grading on the stiffness of concrete. The grading curves of two types of sand are shown in Figure 3.6.

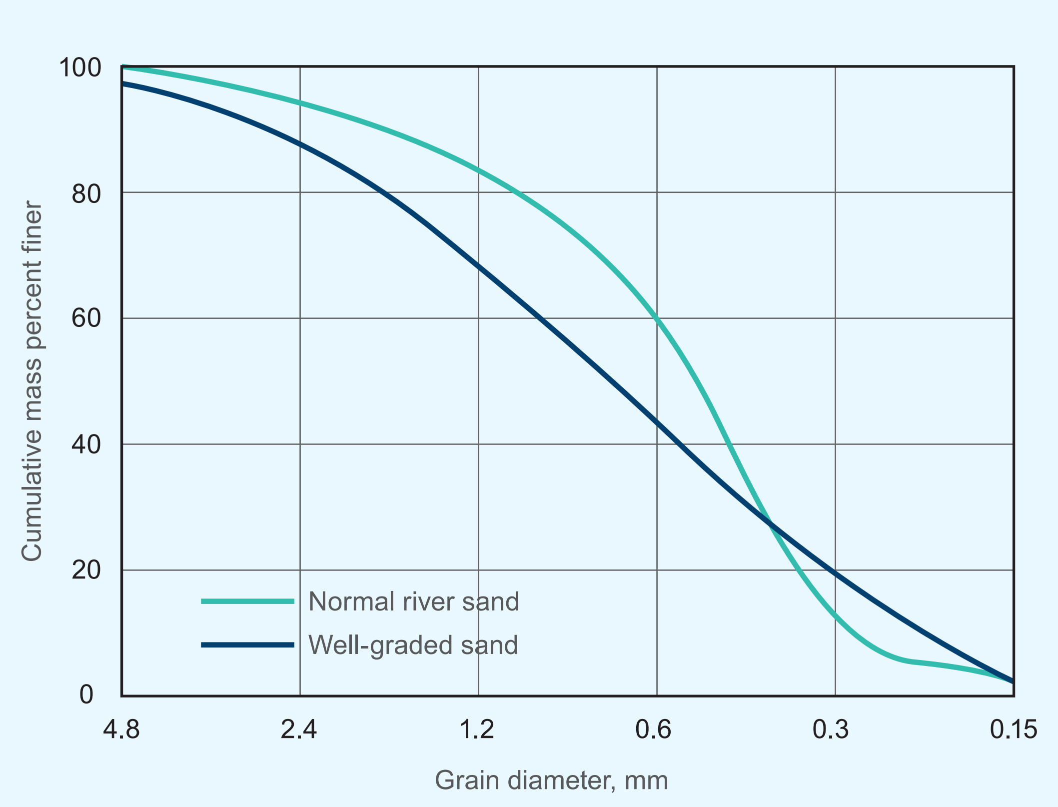


Figure 3.6 Grading curves of normal river sand and well-graded sand

The mix proportion of the concrete specimens was the same as Table 3.3 C. The only difference between these two batches was the grading of fine aggregate: one is normal river sand and the other one is well-graded sand. The slump test results showed that concrete mixture with well-graded sand has the slump value of 180 mm, which was a little larger than that with normal river sand. It can be seen from Figure 3.7 that fine aggregate with well-graded size distribution led to both higher compressive strength and higher modulus of elasticity, and the increments were approximately four percent. Hence, the highest modulus of elasticity has been improved from 51.45 GPa to 53.53 GPa. Although the preparation of well-graded sand for mixing concrete was not realistic for engineering practice, the importance of fine aggregate grading on the stiffness of concrete has been verified.

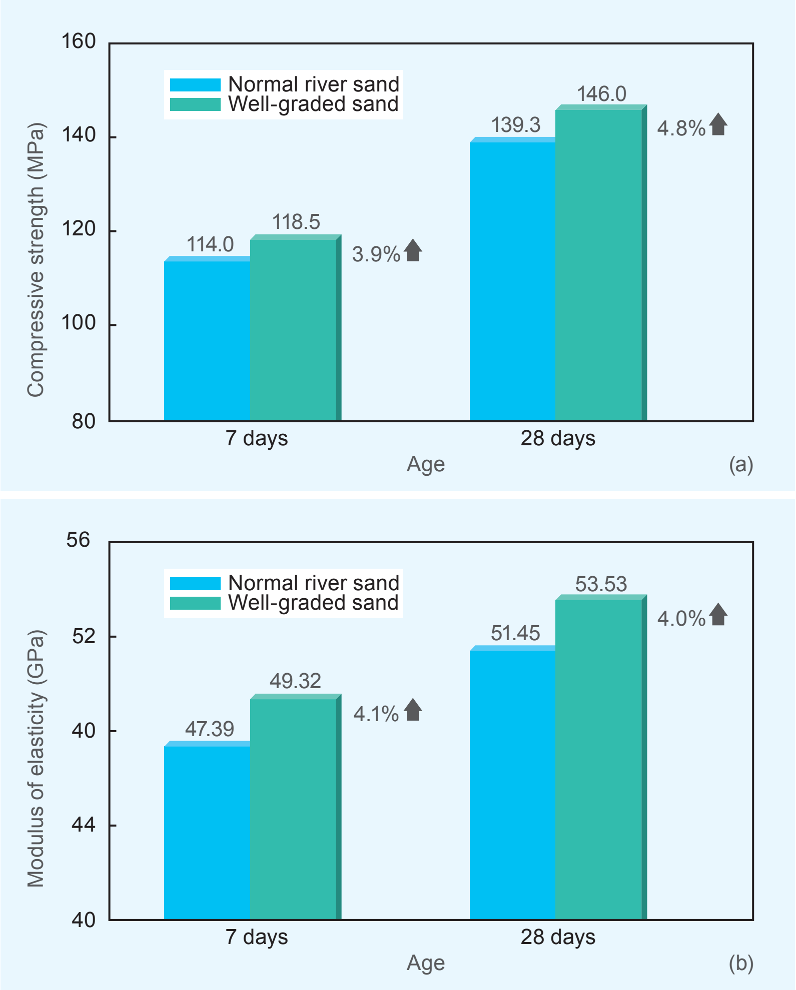


Figure 3.7 Compressive strength (a) and modulus of elasticity (b) of concrete with different size distributions of fine aggregate

vii. Aggregate to cement ratio

According to the equations of theoretical models for prediction of concrete stiffness, the modulus of elasticity of concrete increases with the volume fraction of the aggregate since the modulus of aggregate is always greater than the modulus of cement matrix for normal or high-strength concrete. Therefore, increasing aggregate/cement (A/C) ratio may be helpful to develop the high modulus concrete. The original aggregate/cement ratio of the high modulus concrete was 3.03, and another batch of concrete specimens with larger *A/C* ratio of 3.34 was prepared to study whether improving *A/C* ratio is effective to enhance concrete stiffness. Fine aggregate used in these two batches of specimens was well-graded river sand.

Test results indicated that neither compressive strength nor modulus of elasticity could be enhanced by increasing aggregate to cement ratio. That means using more aggregate and less cement matrix cannot improve the concrete stiffness. There may be two main reasons for this phenomenon. The first one is that concrete mixture with more aggregate has lower fluidity so that there are more air bubbles inside the specimen to reduce the strength and stiffness. The other reason may be related to the interfacial transition zone between aggregate and cement paste. Since *A/C* ratio is increased, there is no adequate cement matrix surrounding aggregate particles. Bad ITZ (Interfacial Transition Zone) may hinder the stress transfer inside the specimen to decrease the strength and may cause early micro-cracks to decrease the stiffness. Bad ITZ also means more porous nature between aggregate and cement matrix, which may result in large deformation occurrence. Therefore, the conclusion can be drawn that the original *A/C* ratio of 3.03 is suitable for making high modulus concrete.

viii. Mineral admixtures

The proportions of raw materials used for mixing concrete have been optimized, and the highest modulus of elasticity of concrete is 53.5 GPa. With the deepening of this study, some mineral admixtures such as metakaolin and nano-silica were used to further improve the packing of cementitious material particles. Metakaolin has the particle size less than 2 micron, which is significantly smaller than cement particles, though not as fine as silica fume. Thus, it can fill the voids between cement and silica fume to form denser structures. Nano-silica is a kind of nano particles that has the particle size around 12 nm, which is even smaller than condensed silica fume, and is the smallest pozzolanic material in the concrete mixture. It is reported that using metakaolin and nano-silica can increase the compressive strength and enhance the durability of hardened concrete. In this study, 10% of metakaolin and 1% of nano-silica were added into concrete mixture to partially take place of cement. During mixing, it was found that the lowest water/cement ratio of 0.20 could not be applied any more, since larger surface area of metakaolin and nano-silica made the fresh concrete too cohesive. Therefore, the water/cement ratio had to be increased to 0.23 to meet the workability requirement. It should be pointed out that both metakaolin and nano-silica were added to the mixer directly without any pretreatment. The mix proportions are listed in Table 3.4.

Table 3.4 Mix proportions of concrete with different mineral admixtures

Specime No.	OPC	PFA	Meta-kaolin	CSF	Nano-SiO_2	Volcanic 20mm	Volcanic 10mm	River sand	Water	Glenium SP8S	*w/c*
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	
Reference	440	90	--	55	--	530	430	740	135	18	0.23
MK	380	90	60	55	--	530	430	740	135	18	0.23
Nano-SiO_2	435	90	--	55	5	530	430	740	135	18	0.23

The compressive strength and modulus of elasticity test results are shown in Figure 3.8. It is obvious that under the same water/cement ratio, concrete mixture with 10% metakaolin or 1% nano-silica had both higher compressive strength and modulus of elasticity than the reference group. Particularly in the concrete mix with 1% nano-silica, the compressive strength increased dramatically to 137 MPa, which had 18% increment. The main reason for this improvement is that silicon dioxide, the main component of both metakaolin and nano-silica, improves concrete performance by the packing effect and by reacting with calcium hydroxide to form secondary C-S-H. However, the highest strength and modulus still cannot exceed the values of concrete with water/cement ratio of 0.20, which means that reducing water is a more effective approach to enhance concrete stiffness.

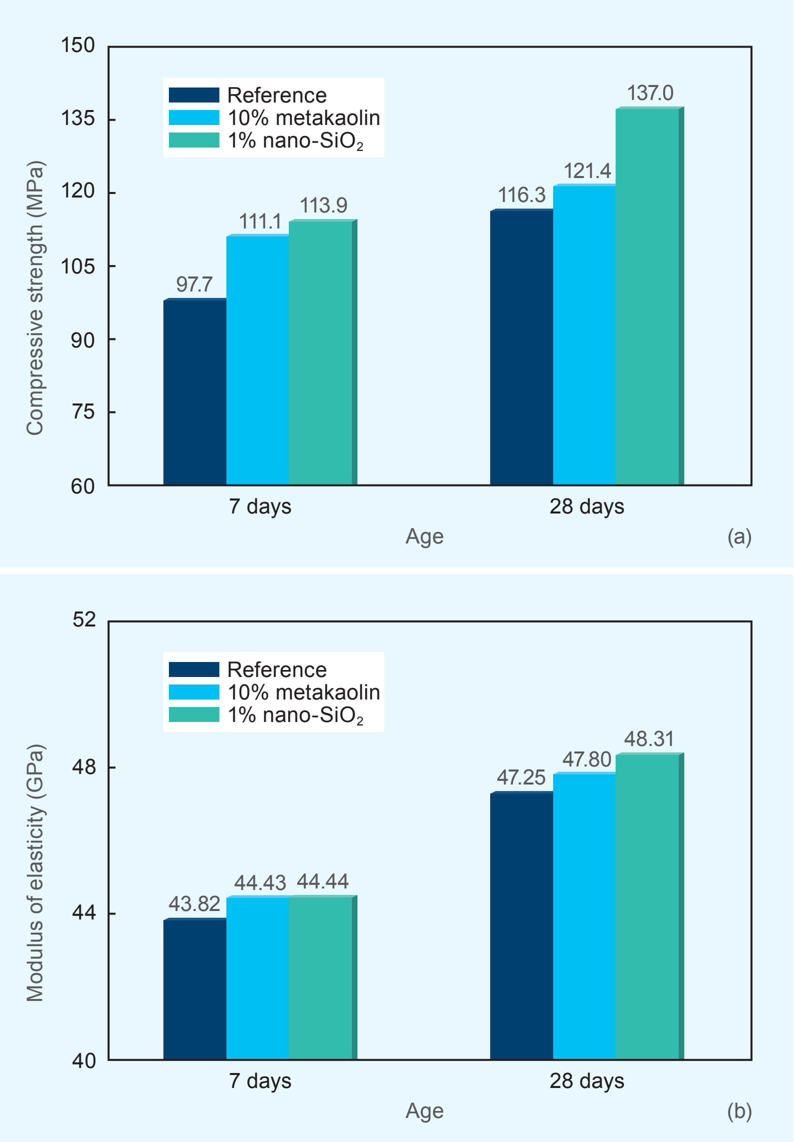
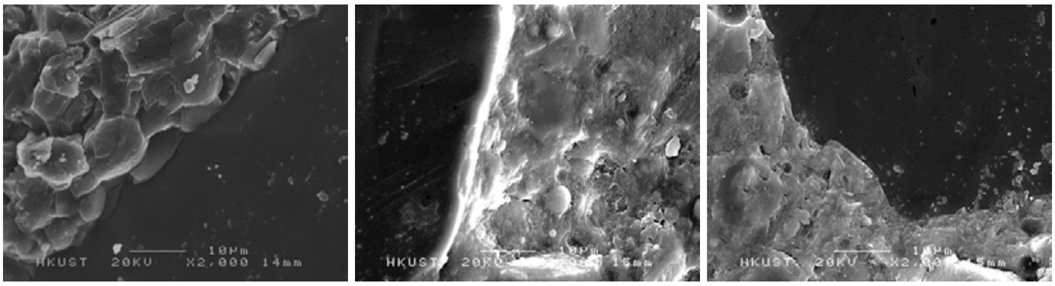


Figure 3.8 Compressive strength (a) and modulus of elasticity (b) of concrete with different mineral admixtures

The interfacial transition zone is generally considered the weakest link of the concrete chain. It has a strength-limiting effect in concrete and concrete always fails at a considerably lower stress level than either of the two main components. The structure of the transition zone, especially the volume of voids and microcracks, has a great influence on the strength or the elastic modulus of concrete. In a composite material, the transition zone serves as a bridge between two components: the bulk matrix and the aggregate particles. Even when the individual components are of high stiffness, the stiffness of the composite may be low because of the broken bridge. To investigate the interfacial transition zone in the concrete mixtures, scanning electron microscope (SEM) was applied. SEM images of ITZ in the concrete mix with mineral admixtures are shown in Figure 3.9. The three images are in the same magnification. It can be seen that there are some air voids along the ITZ in the concrete mix with no extra mineral admixtures. In Figure (b) and (c), it is obvious that the ITZ has better quality and denser structure, hence, concrete with 10% metakaolin or 1% nano-silica has higher modulus of elasticity. It proves the theory that transition zone is a key factor to influence the concrete stiffness, and mineral admixtures such as metakaolin and nano-silica can form better transition zone inside the concrete by packing effect and chemical reactions.



(a) (b) (c)

Figure 3.9 SEM images of ITZ in the concrete mixtures with mineral admixtures: (a) reference; (b) 10% metakaolin; (c) 1% nano-SiO_2

3.1.3 Ultrasonic mixing technique

When it comes to improvements in concrete properties, mixing technology is as important as concrete composition. Mixing is an essential step in the production of uniform, high quality concrete. Previously, people poured the admixtures in water and used ultrasonic technique to disperse the particles evenly into the water first. The solution was then added into the mixer to mix with other raw materials to form fresh concrete. In this study, ultrasonic technique has been used during the mixing process. A special sonicator is designed and manufactured for the mixer in the material lab so that the two equipment can work together to improve the mixing efficiency. The sonicator has the power of 2000 watt, which is quite strong to generate the ultrasonic wave and make it pass through the fresh concrete. The detailed information of the sonicator is shown in Figure 3.10 and the experiment apparatus is also illustrated.

Figure 3.10 Experimental setup for ultrasonic mixing technique

At first, concrete mixture with water/cement ratio of 0.20 was mixed by using this technique. However, due to the deagglomeration, more water was absorbed by binder particles so that the fluidity was quite different from the previous mixture. The state of fresh concrete could not satisfy the pumping requirement no matter how much superplasticizer was added. Much concrete accumulated in the front of the sonicator probe when the mixer rotated because the fresh concrete was too viscous. Thus, the water/cement ratio had to be increased to 0.23. The mix proportion was the same as Table 3.3 B. During mixing, it was found that many air bubbles came out from the fresh concrete when the sonicator was turned on. Since the sonicator was specially designed for the mixer, the majority of energy could be released at the top of the probe, which was immersed in the fresh concrete.

The compressive strength and modulus of elasticity test results are shown in Figure 3.11. It is obvious that concrete mixture with ultrasonic mixing technique had both higher compressive strength and modulus of elasticity than that without ultrasonication. It verified that ultrasonic mixing technique is an effective approach to enhance concrete mechanical properties although it requires more energy.

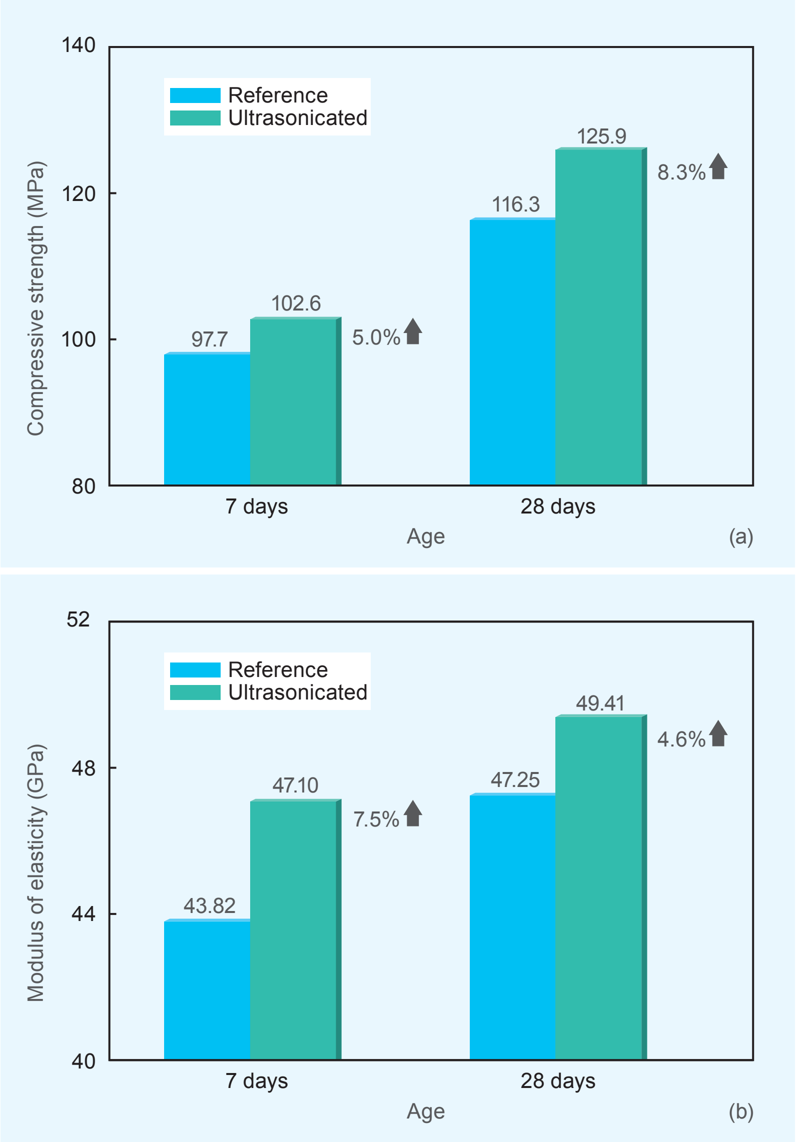


Figure 3.11 Compressive strength (a) and modulus of elasticity (b) of concrete with/without ultrasonic mixing technique

3.2 Dimensional Stability Properties

Figure 3.12 shows the autogenous shrinkage of concrete specimens with different modulus of elasticity from 1 day until the age of 28 days. The test results indicated that the autogenous shrinkage increased fast at first seven days and then the growth rate decreased. Concrete with the highest modulus of elasticity showed the largest autogenous shrinkage which was approximately 220 micro-strain. However, C45 normal concrete only had about 150 micro-strain autogenous shrinkage. Previous investigators also reported such a phenomenon that concrete with lower water to cement ratio had larger autogenous shrinkage.

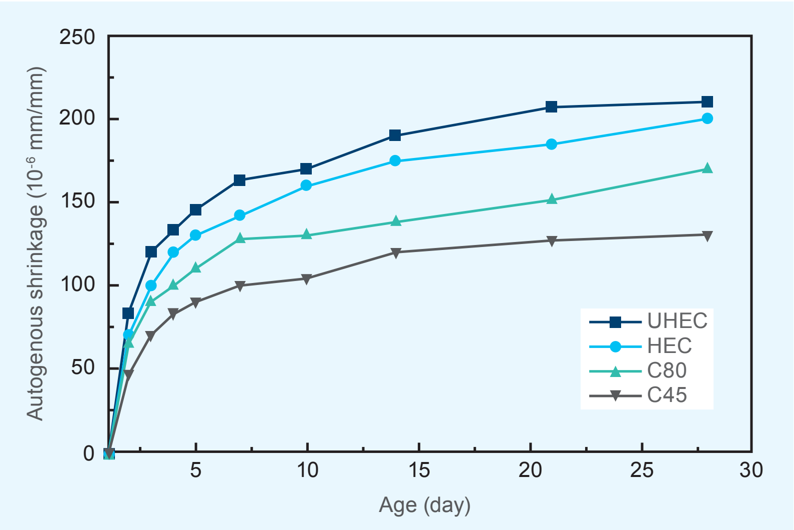


Figure 3.12 Autogenous shrinkage of concrete with different modulus

However, the total shrinkage measured on the unsealed specimens showed different trend (Figure 3.13). The total shrinkage consists autogenous shrinkage from 24 h (Figure 3.12) and drying shrinkage due to weight loss to the outside environment. The results indicated that C45 had the largest total shrinkage over 700 micro-strain while the ultra-high modulus concrete only had 400. The detailed strain of drying shrinkage can be calculated by deducting autogenous shrinkage from total shrinkage and is shown in Figure 3.14. The drying shrinkage of UHEC is less than 40% of C45, which means that the relative humidity in outside environment has much less effect on the drying shrinkage of high modulus concrete.

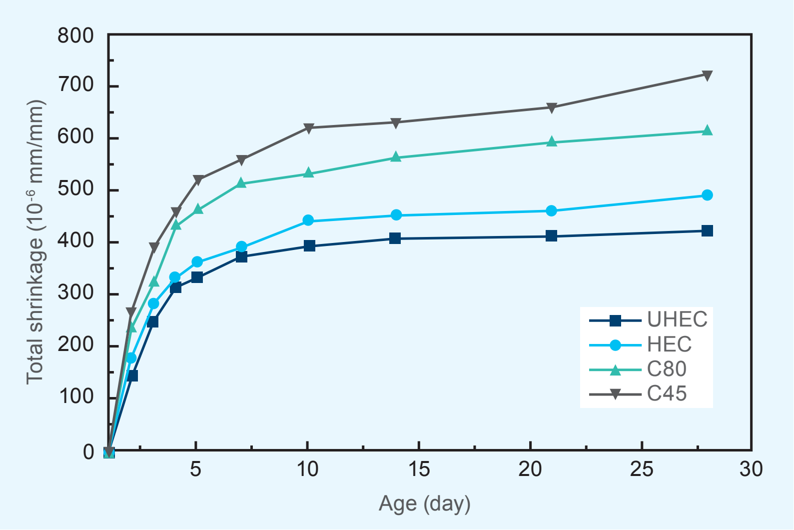


Figure 3.13 Total shrinkage of concrete with different modulus

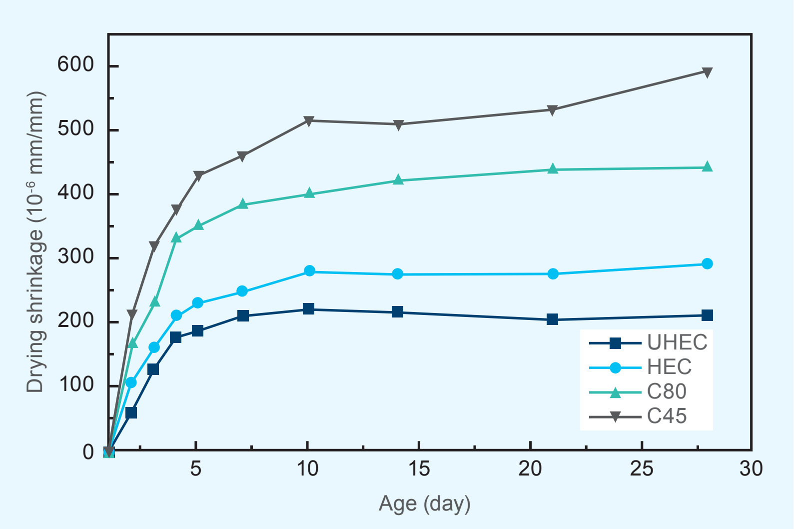


Figure 3.14 Drying shrinkage of concrete with different modulus

Along with drying shrinkage test, the weight loss of concrete specimens was also recorded to monitor the water evaporation (Figure 3.15). At 21 days after casting, the weight loss of ultra-high modulus concrete under 23°C and 55% RH was less than 1%, while this value of C45 was over 2%. It verified the advantage of high modulus concrete against dry environment.

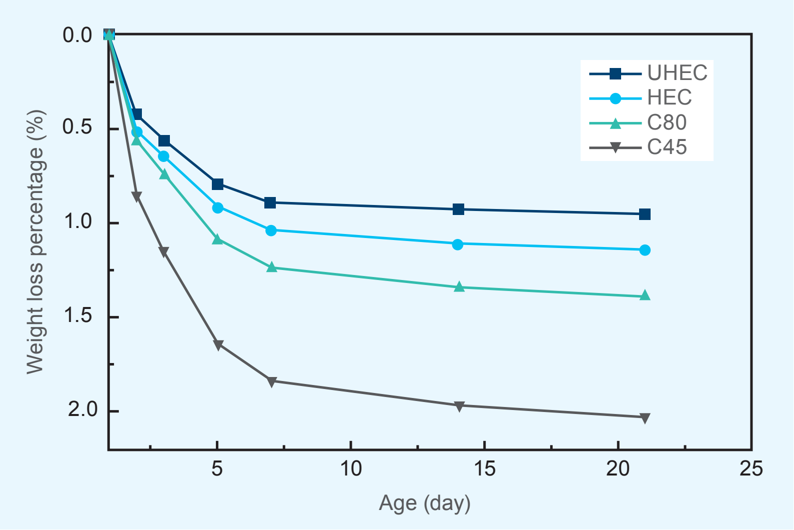


Figure 3.15 Weight loss of concrete with different modulus

The results of creep test started from 2 days after casting are shown in Figure 3.16. A constant force of 40 kN was applied on 100-mm diameter cylinders. The specific creep, which equals to creep strain divided by stress, can be compared among four concrete specimens with different stiffness. C45 sample had a creep value over 1100 micro-strain at 28 days, which was much larger than unloaded specimen. UHEC had much better performance and its creep was only roughly 500 micro-strain.

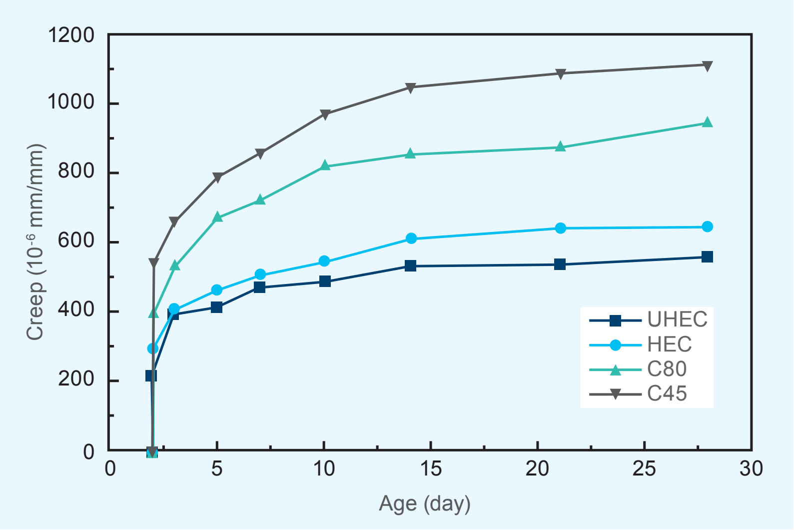


Figure 3.16 Creep of concrete with different modulus

3.3 Application of High Modulus Concrete on Structural Beams

This report just takes mid-span deflections of test beams as an example for analysis. The load-deflection curves were automatically generated during the test. The ultimate resistance of steel reinforced concrete beams was slightly increased with an increase of concrete grade or concrete stiffness. The load capacity of the UHEC concrete beam was approximately 30% higher than that of C45 concrete beam. Also, it is obvious that steel fibers contributed to higher ultimate load. In Figure 3.17, msf means micro steel fiber and sf stands for normal steel fiber. Micro steel fiber has much higher length/diameter ratio than normal one. And the digit in front of the fiber is the volume fraction of the steel fiber.

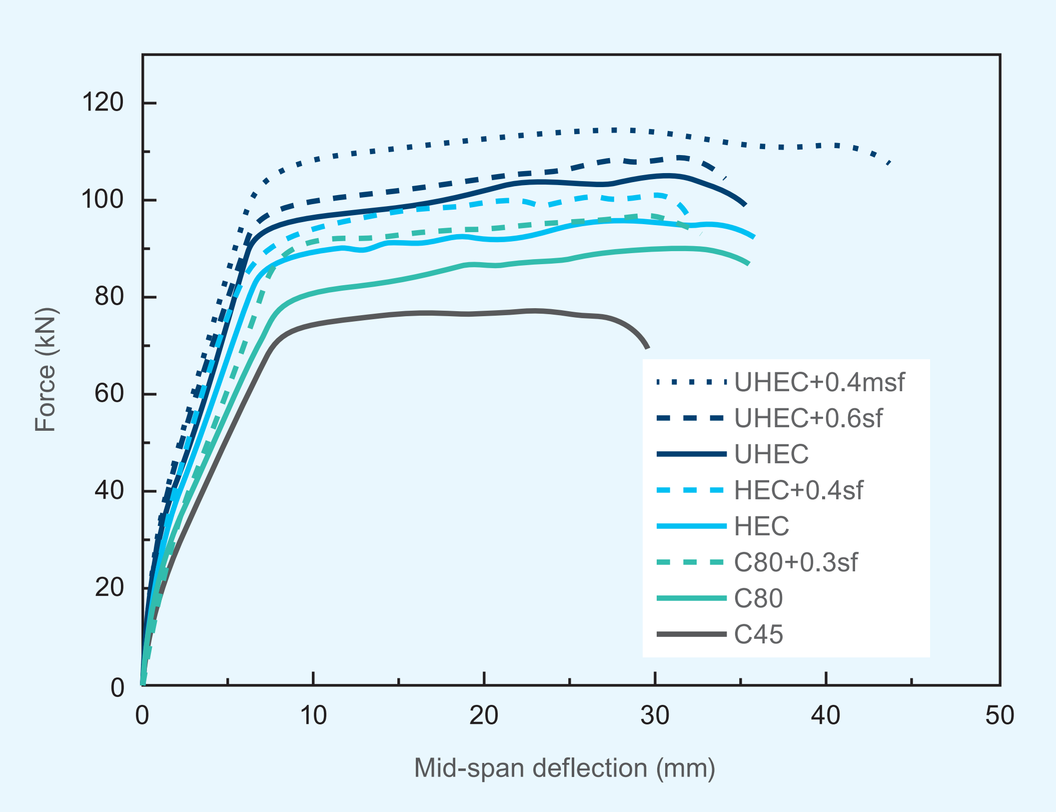


Figure 3.17 Load-deflection curves of reinforced concrete beams

Reinforced concrete beam with higher concrete stiffness had smaller deflection when the rebar in tension zone yielded. For the increment of load capacity by using steel fiber, lower stiffness concrete had more obvious enhancement effect. Compared with normal steel fiber, micro steel fiber had much higher improvement on the load capacity of the beam and the ductility seemed much higher. However, the actual stress level inside the structural member is only half of the ultimate strength or even less in real case. Therefore, 40 kN is selected as the external load under normal service condition to compare the deformation level of beams with various concrete stiffness. Figure 3.18 shows the load versus deflection curves of four reinforced concrete beams without steel fiber. It can be seen from the figure that when the force of 40 kN was applied, the mid-span deflection of C45 beam was 3.60 mm. For C80 beam under the same load, the value was 2.93 mm, which was reduced by 18.6%. However, for ultra-high stiffness concrete and high stiffness concrete beams, the deformation was only 1.67 mm and 2.24 mm, respectively. The deformation decreases were 53.6% and 37.8% compared with that of normal C45 concrete, which indicated dramatic benefits. This results verified the benefits of using high stiffness concrete in producing structural members.

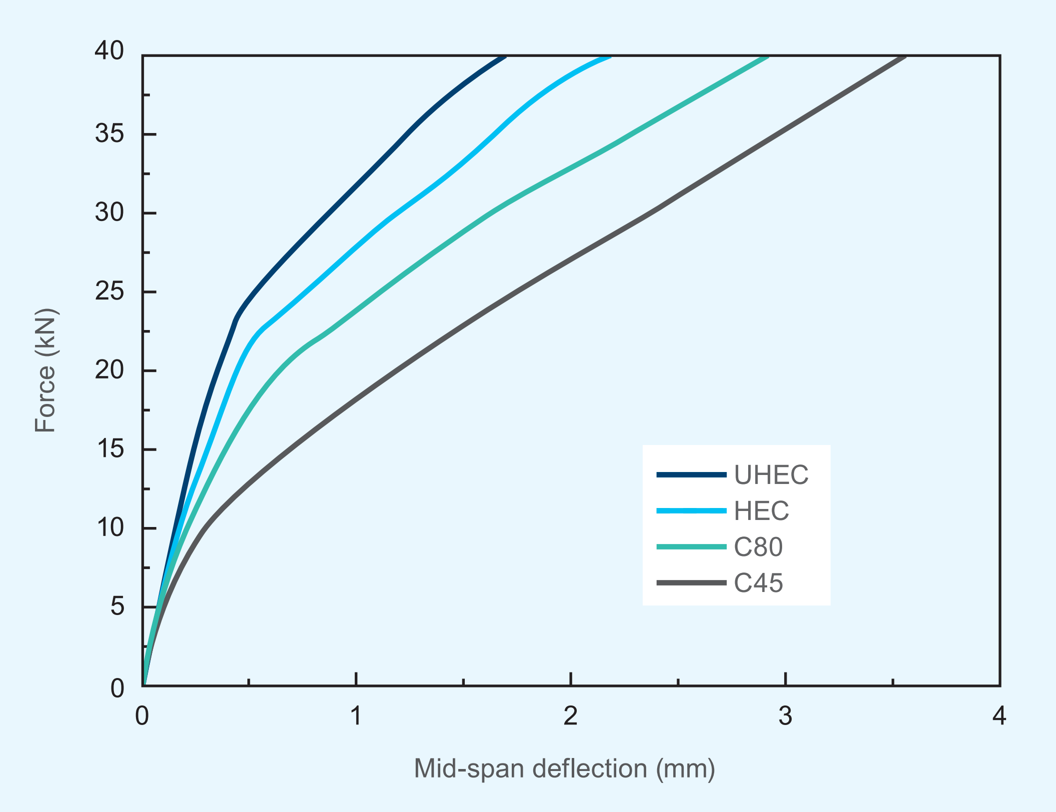


Figure 3.18 Load-deflection curves of beams with max. load of 40 kN

Steel fiber made great contributions in delaying of crack occurrence in reinforced concrete beams. For C80, the concrete is not quite brittle so that the utilization of steel fiber had no obvious effect on crack delaying. However, for high modulus concrete, steel fiber can obviously give concrete a large restraining effect when the cracks appear. The slope of stress-strain curve at early time thus has longer straight part which means there are less cracks in high modulus concrete beams with steel fiber than that without fiber (Figure 3.19).

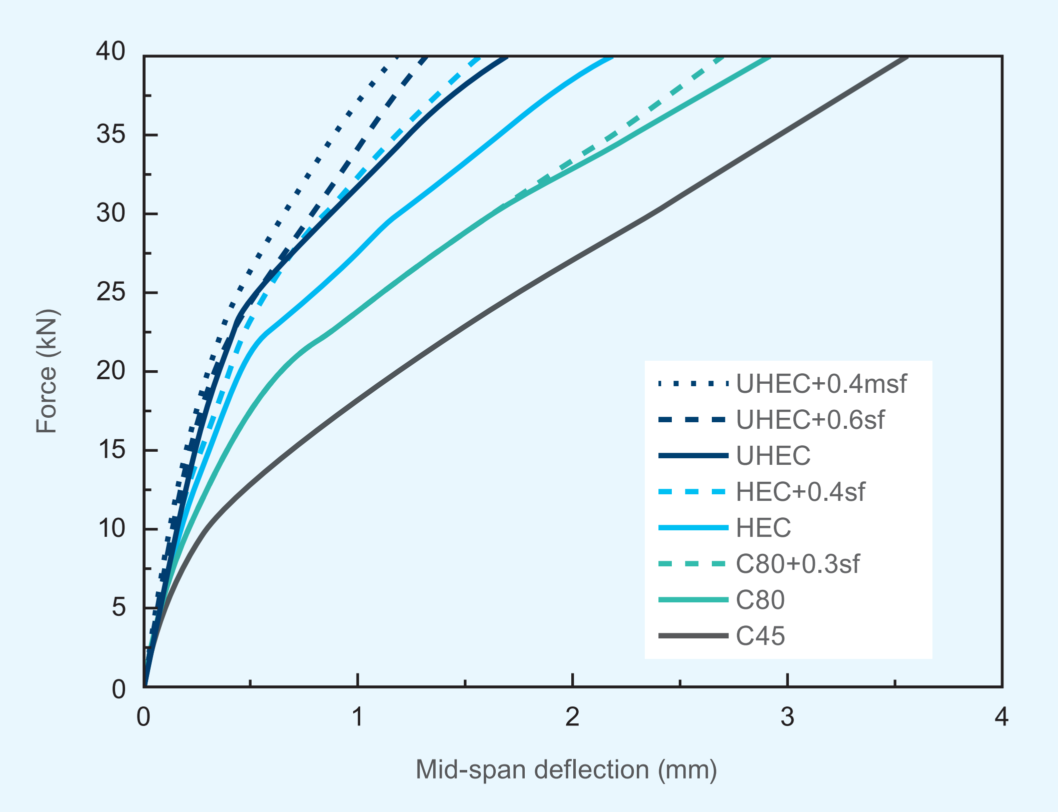


Figure 3.19 Load-deflection curves of beams with/without steel fiber at early time

4 DISCUSSION AND APPLICATION

The highest modulus of elasticity of concrete developed so far is 53.5 GPa and the stiffness enhancement is almost 20% compared with the same strength level concrete in the code of practice. According to the code of Practice for Structural Use of Concrete 2004 Table 3.2, the modulus of elasticity (E_c) and the compressive strength (f_{cu}) have the relationship as follows:

$$E_c = 3.46 f_{cu}^{0.5} + 3.21$$

The solid line in Figure 4.1 shows the strength and stiffness relationship of normal concrete, and the dash line represents 10% enhancement of concrete modulus. It can be seen that the high modulus concrete developed by HKUST was close to 20% higher than normal concrete and the absolute value of compressive strength and modulus of elasticity were also very high.

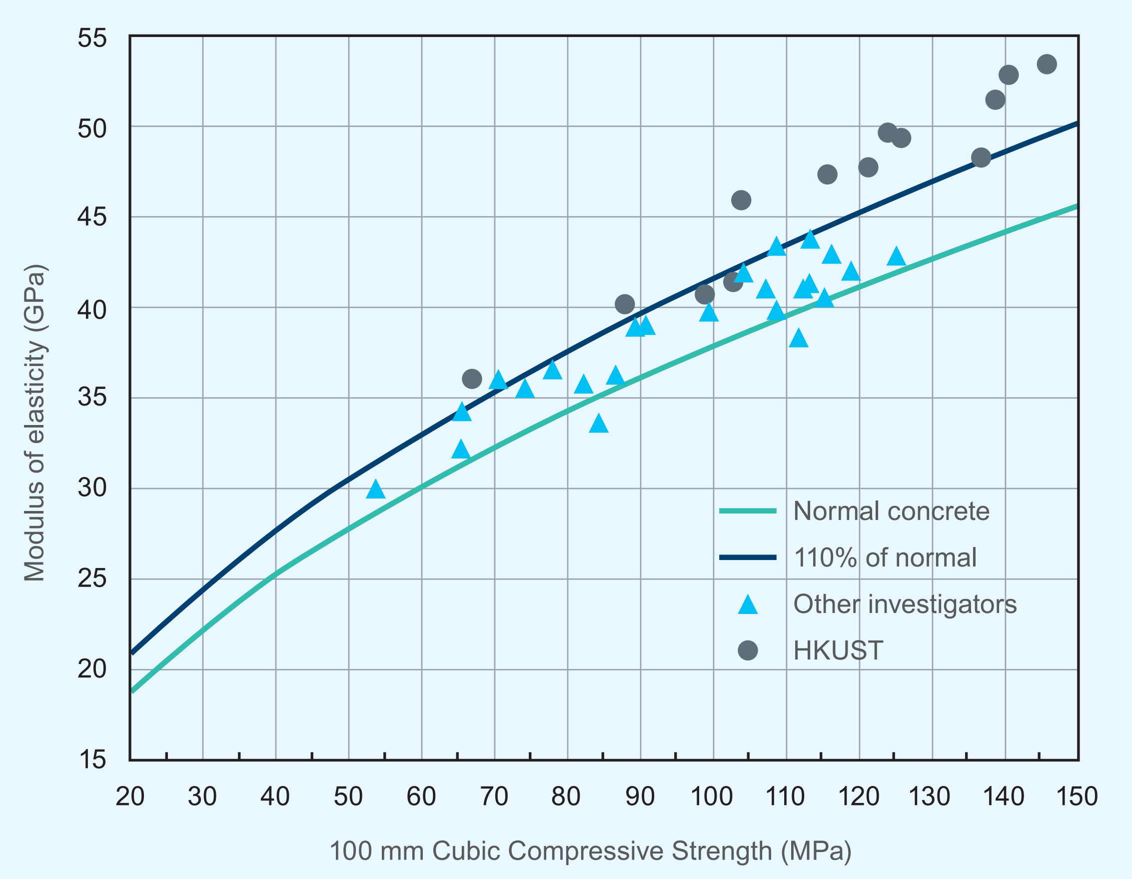


Figure 4.1 Comparison of the relationship between compressive strength and modulus of elasticity (code of practice, other investigators, and HKUST)

Although the unit price of high modulus concrete may be slightly higher than normal concrete, the total amount of concrete consumption will be less if high modulus concrete is applied for real constructions, not to mention more areas can be used by clients. Therefore, high modulus concrete brings tremendous economic benefits.

The much more stable shrinkage and creep performance of high modulus concrete is another advantage compared with normal concrete. When shrinkage and creep occur, large internal stress will be generated inside the structural members and it may even induce cracks. The denser structure, stiffer aggregate and better particle grading lead to smaller shrinkage and creep strain after the concrete gets hardened. It verifies that the high modulus concrete developed is suitable for construction of tall buildings.

Columns of tall buildings are always under uniaxial compression load and the stress condition is like cylinders in modulus of elasticity test. There is no doubt that the vertical deformation of high modulus concrete column is smaller than that of normal concrete. For reinforced concrete beams, although the bending moment is mainly carried out by steel rebar, high modulus concrete result in smaller deflections according test results. Conclusions can be drawn that high modulus concrete can reduce structural deformation in both beams and columns, and can bring many advantages in design, construction and maintenance of tall buildings.

5 CONCLUSIONS AND THE WAY FORWARD

Through the conduction of this project, the following conclusions can be drawn:

First of all, the concrete mix was optimized to achieve high modulus of elasticity. It was found that there was an approximately linear relationship between cylindrical and cubic compressive strength so that the ultimate stress of each shape of specimen can be predicted by the other one. The factors which affected the modulus of elasticity of concrete, including types of coarse and fine aggregate, sand ratio, silica fume, water/cement ratio, grading of sand, aggregate/cement ratio and mineral admixtures were analysed respectively. It was found that concrete with volcanic rock as coarse aggregate and river sand as fine aggregate had higher stiffness than that with granite rock and crushed stone fines. Sand ratio around 43% and silica fume content about 10% was suitable for making high modulus concrete. Water to cement ratio should be minimized so that the lowest porosity and highest stiffness of cement paste can be achieved. Meanwhile, well-graded size distribution of river sand was better than uniform grading when developing high modulus concrete, and the aggregate to cement ratio cannot be so large because there must be adequate cement matrix surrounding aggregates. Mineral admixtures such as metakaolin and nano-silica led to high modulus of elasticity of concrete, but the water/cement ratio had to be sacrificed. At last, ultrasonic mixing technique was used for making high modulus concrete, and it was verified to be useful for concrete stiffness. The highest modulus of elasticity of concrete has reached 53.5 GPa, which is much higher than normal concrete in practice.

Then, shrinkage and creep properties of concrete were studied on four concrete mixtures including C45, C80, high modulus and ultra-high modulus concrete. It was found that high modulus concrete developed previously had much smaller drying shrinkage value although its autogenous shrinkage was a little larger than normal concrete. Therefore, the total shrinkage of high modulus concrete was still smaller than that of normal concrete. High modulus concrete also had smaller creep strain than normal concrete under the same stress level.

In the end, high modulus concrete was applied in producing structural members. The ultra-high modulus concrete increased the load capacity of reinforced concrete beam by approximately 30% than normal concrete. At actual service stress level, the mid-span deflection of ultra-high modulus concrete beam was roughly half of normal concrete. This deformation reduction verified the benefits of using high stiffness concrete in construction of tall buildings.

So far, three objectives of this research project have been achieved and the experimental results showed great advantages of using high modulus concrete in construction of tall buildings. This high modulus concrete is developed for real structures so that some other properties such as permeability, fire resistance and alkali-silica reaction risks need to be tested in the future before being utilized in practice.

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