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การประชุมใหญ่ทางวิชาการประจำปี 2535
จัดโดย วิศวกรรมสถานแห่งประเทศไทย ในพระบรมราชูปถัมภ์

เรื่อง

บทบาทของมวลหยาบต่อคอนกรีตกำลังสูงในประเทศไทย

โดย

สุดา เถลิงพงษ์
เอนก ศิริพานิชกร
เมธี เวชารัฒนา

RP-73

บทบาทของมวลหยาบต่อคอนกรีตกำลังสูงในประเทศไทย

INFLUENCE OF AGGREGATE ON HIGH STRENGTH CONCRETE IN THAILAND

สุดา เถลิงพงษ์
SUDA TALUNGPONG
Grauate Student

เอนก ศิริพานิชกร
ANEK SIRIPANICHKORN
Lecturer

Department of Civil Engineering
King Mongkut's Institute of Technology Thonburi
Bangmod, Rasburana, Bangkok 10140, Thailand

and

เมธี เวชารัตนา
METHI WECHARATANA
Professor
Department of Civil and Environmental Engineering
New Jersey Institute of Technology
Newark, New Jersey 07102, U.S.A.

บทคัดย่อ

เนื่องจากการเติบโตทางเศรษฐกิจทำให้มูลค่าที่ดินในกรุงเทพฯมีค่าสูงขึ้นอย่างมาก ดังนั้นอาคารที่สร้างขึ้นใหม่จึงมักเป็นอาคารสูง ในปัจจุบันนี้อาคารสูงขนาด 40 ถึง 100 ชั้นสามารถพบเห็นได้ทั่วไปในย่านใจกลางธุรกิจของกรุงเทพมหานคร การก่อสร้างอาคารสูงจำเป็นต้องใช้วิธีการออกแบบและก่อสร้างที่ซับซ้อนขึ้น การใช้มาตรฐานการออกแบบในปัจจุบันอาจจะไม่เหมาะสม และมักทำให้สิ้นเปลืองค่าก่อสร้าง เพราะมาตรฐานดังกล่าวนั้นเหมาะสำหรับอาคารที่ไม่สูงมากนัก ถึงแม้ว่าคอนกรีตกำลังสูงจะมีราคาแพงกว่าคอน-กรีตธรรมดา แต่เมื่อเปรียบเทียบกับราคาโดยรวมของงานอาคารสูงแล้ว โครงการที่ใช้คอนกรีตกำลังสูงอาจจะมีราคาต่ำกว่าโครงการที่ใช้คอนกรีตธรรมดา

โดยทั่วไป บริษัทผู้ผลิตปูนซิเมนต์ หรือคอนกรีตในประเทศไทยจะมีส่วนผสมสำหรับคอนกรีตกำลังสูงของตนเองโดยเฉพาะ ค่าของคอนกรีตกำลังสูงที่ผลิตได้อยู่ในช่วงระ-หว่าง 500 ถึง 800 กก./ซม.^{2} การผลิตคอนกรีตกำลังสูงในประเทศไทยในช่วงแรกๆ นั้นจะใช้ไมโครซิลิกา (Microsilica) หรือ ซิลิกาฟูม (Silica Fume) เป็นสารผสมเพิ่มในคอนกรีต เพื่อทำให้กำลังรับแรงของคอนกรีตสูงขึ้น คอนกรีตกำลังสูงนี้มีราคาประมาณ 5000 บาทต่อลูกบาศก์เมตร ซึ่งถือว่าแพงมาก ดังนั้นการพัฒนาคอนกรีตกำลังสูงจึงมุ่งเน้นไปยังการใช้เถ้าถ่านหิน และ Superplasticizer การผลิตคอนกรีตกำลังสูงจะด้วยวิธีการใดๆก็ตาม ผู้ใช้คอนกรีตควรต้องทราบถึงคุณสมบัติตลอดจนลักษณะการวิบัติของคอนกรีตเหล่านี้ให้ถ่องแท้เสียก่อนที่จะนำไปใช้ในงานอาคารสูงต่างๆ

บทความนี้ เสนอผลงานการวิจัยคุณสมบัติของคอนกรีตกำลังสูงที่ทำการทดลอง ณ สถาบันเทคโนโลยีพระจอมเกล้าธนบุรี การวิจัยจะเน้นถึงบทบาท และชนิดของมวลรวมหยาบที่มีผลต่อคอนกรีตกำลังสูง รวมถึงลักษณะการวิบัติของคอนกรีตชนิดนี้ด้วย ผลการทดลองแสดงให้เห็นว่า หินแกรนิต และหินบาซอลท์จะให้กำลังที่สูงกว่าคอนกรีตที่ใช้หินปูนเป็นมวลรวมหยาบ นอกจากนี้ยังพบว่าการ Capping มีผลอย่างมากต่อค่ากำลังของคอนกรีตกำลังสูง

SUMMARY

Land cost escalation in Bangkok metropolitan area have pushed the building industry and developers to shift into high-rise building of 40 to 91 storeys. This new era demands more advanced building design and construction technology. The obsolete design code presently in use is inefficient and not cost effective for major real estate investment. High strength concrete technology has been introduced into the Thai's building industry with the expectation of overall cost saving of the project. Major cement and concrete suppliers in Thailand have all attempted to develop their own formulation of high strength concrete. In so far, the strengths of these concretes are in the range of 500 to 800 ksc which cost about 4500 to 5000 baht per cubic meter. The expensive ingredients incorporated into the high strength concrete are microsilica and high dosage of superplasticizer. These microsilica concretes were generally considered to be too expensive. Newly developed high strength concrete then emphasizes more on the use of fly ash and superplasticizer. No matter what additive is to be used, the users need to thoroughly understand the behavior and failure mechanism of these high strength concretes prior to its placement in all the high-rise buildings.

This paper presents the results of an on-going investigation conducted at the King Mongkut's Institute of Technology Thonburi on the mechanical properties and failure mechanism of high strength concrete. The study was focused on the influence of various coarse aggregates on high strength concrete. Failure mechanism and the effect of tie reinforcement were also investigated. The results indicate that granite commonly provides higher strength concrete than conventional crushed limestone aggregate and basalt. Also observed is the significant effect of capping on the measured strength of these concretes. Lateral reinforcement shows no influence on the ultimate compressive strength of concrete based on the type of conventional testing machine available in Thailand. However, it is believed that its enhancement is more on the improved ductility or post-cracking behavior of the composites.

INTRODUCTION

Development of high strength concrete first started in 1977 by a task force on high strength concrete in Chicago high-rise buildings [1]. Then, in 1979, an international workshop on high strength concrete was organized at the University of Illinois at Chicago Circle to define and provide direction of research need for the development of high strength concrete [2]. The result out of the workshop led to the creation of the ACI 363 -committee on high strength concrete.

The definition of high strength concrete was first set to be any concrete with strength higher than 6,000 psi (400 ksc) [3]. Since then many high strength concretes have been used in new high-rise building projects. The strength of these concretes gets higher and higher. Several buildings in Seattle area have used concrete of up to 19,000 psi (1,300 ksc) [4]. The world's tallest reinforced concrete building, the 311 Wacker Drive, also contains an 850 ksc high strength concrete. In Thailand, designers of many new high-rise buildings are considering using high strength concrete in their projects. The range of these concrete is about 500 ksc. Since the product is new to Thai engineers and designers, debate over the cost of these high strength concretes seems to hold back the actual implementation of high strength concrete in Thailand. Furthermore, many designers do not fully understand the performance of these high strength concrete. The design concept presently in use depends solely on the strength of concrete alone. Very little effort was made to thoroughly account for other important sensitive material properties.

Development of high strength concrete lies solely in the hand of concrete suppliers with very little participation from designers or structural engineers of the project. More interestingly, selection of mix proportions and raw materials was based on a very low quality assurance process where coarse and fine aggregates were not thoroughly evaluated for its suitability. It seems that engineers of most concrete suppliers do not have any choices or control over the type and quality of aggregates used. The mix proportion used, in general, was rather rich in cement content with poor quality of aggregates. Problems of quality control at the construction site remain the dominating factor governs the final condition of any type of concrete placed. For instance, if concrete delivered to the site did not meet the workability requirement, often water was added to resolve the problem. Obviously, such a practice is not acceptable especially when high strength concrete is to be used in the project.

High strength concrete can be produced in many ways. The general principles are reducing the water to cement ratio to about 0.26 to 0.30, and adding pozzolanic materials such as microsilica and fly ash. To maintain proper workability, high dosage of superplasticizer is added. The key concept is to reduce void in concrete and enhance the strength of the matrix. Once the strength of the matrix is improved up to a certain level, it is the strength and durability of the aggregate that further governs the performance of concrete. To achieve high strength concrete of 11,500 to 14,000 psi (800 to 1,000 ksc), the coarse aggregate plays a major role in the strength development of these high strength cement composites. A careful screening and selection of the type of coarse aggregate to be used is often the very first step taken. As mentioned earlier that this critical step does not seem to exist in the mix design practice in Thailand, it is then the objective of this study to demonstrate the role and influence of coarse aggregate on the strength and performance of high strength concrete.

In addition, the role of lateral reinforcement and type of microsilica used on the strength development and property of concrete was also investigated.

EXPERIMENTAL PROGRAM

The high strength concrete developed in this study was based on the addition of microsilica. There were two types of microsilica used in this study, one in the powder form and the other in the slurry condition. The chemical composition of the powder-typed silica fume is presented in Table I. The amount of microsilica added was 10, and 12%. Three types of coarse aggregates, namely crushed limestone, basalt, and granite, were used to evaluate the influence of coarse aggregate on the strength of concrete. The size of coarse aggregate was also investigated using two sizes (3/4" and 3/8") from each type of the selected aggregate. More details on the physical and mechanical properties of these coarse aggregates can be obtained in Ref.[5].

Mix Proportions

The type of cement used was the standard type I portland cement. The fine aggregate selected was the ordinary river sand with a fineness modulus of about 2.8. The water to cement ratio was kept constant at 0.28. All high strength concrete mixes contain high dosage of superplasticizer to provide for proper workability.

The mix proportions selected in this study can be categorized into one mix of normal strength concrete (Mix I) which was used as reference and three mixes of high strength concrete (Mix II, III, and IV). Details of each mix proportion can be found in Table II.

Table I Chemical Compositions of Silica Fume Powder Type)

SiO_2	92.0-96.0
Fe_2O_3	0.15-0.30
Al_2O_3	0.01-0.15
MgO	0.01-0.10
Na_2	0.10-0.20
K_2O	0.01-0.30
C	1.00-6.00
P_2O_5	0.05-0.15
CaO	0.01-0.05

Table II Mix Proportions

Mix Proportion (kg/m^3)							
Mix	Cement	Sand	Aggr.	Water	w/c	Micro-silica	Admixture
I	350	780	1150	178.5	0.51	0	750cc
II	500	600	1300	140	0.28	10%	14 kg
III	500	600	1300	140	0.28	12%	14 kg
IV	500	600	1300	140	0.28	12%	14 kg

Note that the silica fume used in Mix II and III was the powder type whereas the one in Mix IV was in the slurry form. Mix I is a standard mix of normal strength concrete provided by one of the concrete suppliers.

Mixing Procedure

All coarse aggregates were first washed to remove dust and dirt particles. Dry coarse aggregate was then mixed with the fine aggregate in the mixing drum until they were thoroughly mixed together. Cement was dry-mixed with the powder typed silica fume prior to being added into the mixer to further mixed with the aggregates. Then water with 50% of the superplasticizer dosage was added into the mix. The remaining superplasticizer was added into the mixer at a later stage depending on the mix condition. The fresh concrete was then tested for its slump and placed in the molds. Workability of high strength concrete is often a problem to new users who are not familiar with these products and its setting characteristics. However, the use of superplasticizer can easily resolve this problem. It should be noted that most superplasticizers are usually effective for only about 30-40 min. Beyond that period rapid slump loss will take place.

Test Specimen

The type of test specimens used in this study to evaluate the strength of concrete were the standard cylinders of the size 6"x 12", 4"x 8", and 3"x 6". The use of three different sizes of cylinders was meant to study the size effect of test specimen on the observed strength of concrete. All specimens were cast in the steel mold for 24 hours. The specimens were then removed and cured in the lime-saturated water until a day before testing. The specimens were then capped with standard sulfur capping compound at both ends. For high strength concrete, the same sulfur capping was used since there were no high strength capping compounds available in Thailand. All specimens were tested under the conventional hydraulic compression machine for its strength at the age of 3, 7, and 28 days.

Spiral Reinforcement

It is commonly accepted that high strength concrete is more brittle than normal strength concrete. To prevent abrupt catastrophic failure, the ductility of high strength concrete need to be improved. Often, this was done by adding lateral reinforcement. Four different pitches of spiral reinforcement with spacing of 2", 3", 4", and 5" were cast in the high strength concrete cylinders. The effect of lateral reinforcement on the strength of these concretes were evaluated and compared with the unreinforced high strength concrete.

RESULTS AND DISCUSSIONS

Failure Characteristics

High strength concrete generally fails in an abrupt explosive manner. The higher the strength of concrete, the larger the amount of energy stored in the specimen prior to failure. In a manual load-control testing system such as the one used in this study at KMITT, the sudden release of the stored applied energy caused the specimen to split apart and failed under lateral tensile stress. The plane of failure was typically straight vertical, cutting through aggregate. The remains of the test specimen were a few pieces of vertical concrete strips. In some other cases, the failure plane sometimes occurred in an inclined angle similar to the typical shear cone except that the fracture plane slides through each other so fast that crushed concrete powder was found along the fracture plane. This type of failure usually came with an explosion of the sample. Often the remains were simply the top and bottom cones of the specimen.

Abrupt explosive failure usually takes place in the concrete samples with compressive strength greater than 600 ksc. However, in some cases, when sulfur capping was too thick, it often created premature failure due to local crushing of sulfur capping. As a result, the observed ultimate failure strengths were lower than what was supposed to be. Under this instance, the specimen often sustained damage only at around the end. To prevent this type of irregularity, support fixture of the compression machine may have to be modified into a so-called brushed support. Furthermore, high strength capping compound is certainly needed to ensure reliable test results.

The rate of loading obviously plays an important role on the measured strength of the concrete samples. Unfortunately, most commercially available testing machines in Thailand have no accurate closed-loop system for test control. The accuracy of the test results were then at the mercy of the testing technicians who operate these testing machines at each laboratory. In addition, there was no means of obtaining the whole load-displacement curve or stress-strain curve of each concrete sample and the only number obtained from each of the tested sample was the magnitude of the ultimate applied load which will later be converted into the compressive strength.

All test results on the compressive strength of both the normal strength and the high strength concretes are tabulated in Table III. Each of these data was an average of the results from at least three consistent samples. The age, type and size of aggregate were also clearly presented. While some of these results seem fluctuated, this can mostly be attributed to the effect of capping which often failed first. It was clearly observed during the course of this study that if the strength of concrete is higher than 600 ksc with a good quality capping the specimen tends to explode into pieces.

Table III Compression of Normal and High Strength Concrete

Mix No.	Type of Concrete	Age (days)	Compressive Strength (ksc)					
			Granite		Limestone		Basalt	
			3/4"	3/8"	3/4"	3/8"	3/4"	3/8"
1	Normal	3	283	270	277	266	232	229
1	Normal	7	388	354	324	351	243	292
1	Normal	28	460	402	394	381	340	371
2	High	3	640	357	483	360	252	340
2	High	7	802	575	507	450	466	532
2	High	28	713	622	521	656	487	705
3	High	3	573	503	503	359	416	407
3	High	7	762	707	717	634	609	628
3	High	28	845	821	572	707	793	755
4	High	3	700	665	566	586	541	461
4	High	7	734	809	651	750	643	744
4	High	28	804	871	719	820	696	702

To help digesting the information presented in Table III, several comparisons were made to evaluate the effect of aggregate size, the type of aggregate, and the type of microsilica, on the compressive strength of both normal and high strength concretes.

Influence of Aggregate Type

Figs. 1 shows the strength development of normal strength concrete obtained from three different types of aggregate, namely, granite, basalt, and limestone. The point-load-strength index of these aggregates are 139, 192, and 60 ksc for granite, basalt, and limestone respectively. In general, granite was reported to provide a higher strength concrete than basalt and crushed limestone [4]. The results presented in Fig. 1b indicates that for the 3/4" aggregate granite provides the highest compressive strength, with 17% stronger than limestone and 35% stronger than basalt. Limestone aggregate in normal strength concrete performs better than basalt. A visual investigation on the physical composition of basalt found a significant amount of impurity, mostly shale particles, mixed in with the grain of basalt. It is believed that these weak shale components cause the early failure of the concrete matrix. For the smaller size of coarse aggregate (3/8")(Fig. 1a), the same conclusions can be drawn except that there was not significant variation between granite and limestone concrete. Basalt concrete, on the other hand, remains to be the weakest.

Fig. 1a

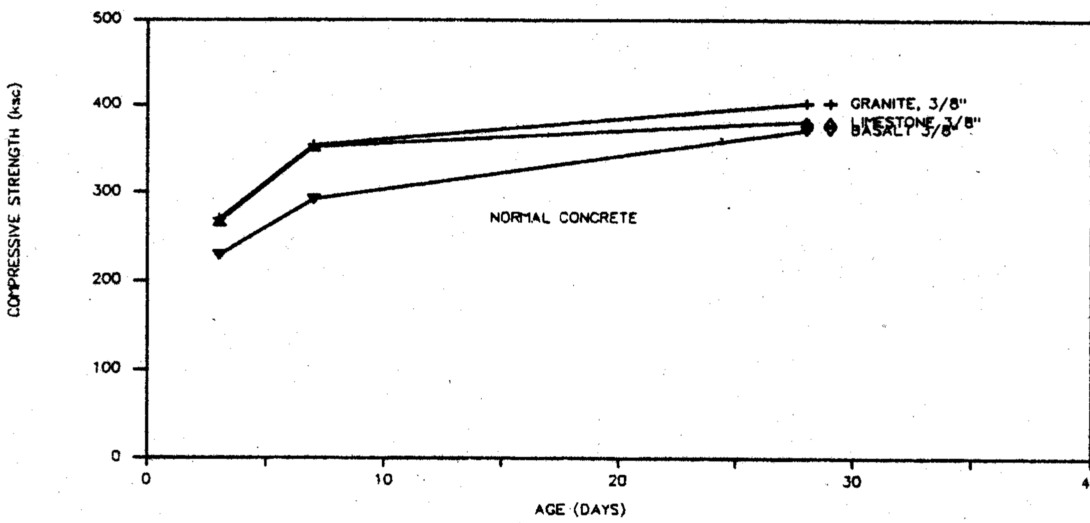


Fig. 1b

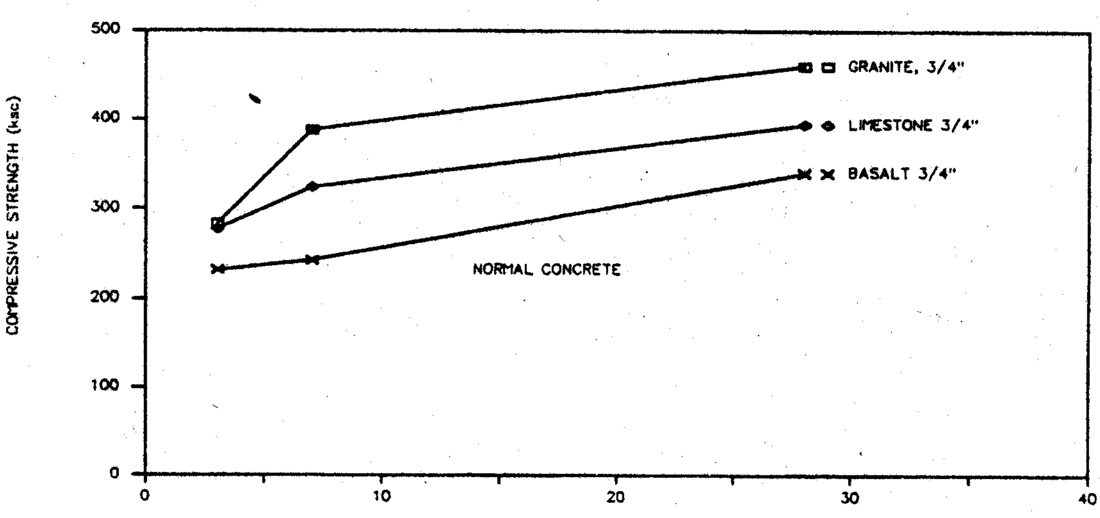


Fig. 1 Effect of Coarse Aggregate on Normal Strength Concrete

Figs. 2, 3, and 4 shows the influence of aggregate on the strength development of high strength concrete. Fig. 2 and 3 are from Mix II and III which contain 10 and 12% of the powder-typed microsilica, respectively. Fig. 4 is for Mix IV which has 12% of the slurry-typed silica fume. With 10% microsilica, the strengths of concrete shown in Fig. 2 for both the 3/4" and 3/8" aggregates are in the range of 500 to 700 ksc. The granite concrete of 3/4" aggregate shows a significant strength development as compared to basalt and limestone concrete of the same size. The 3/8" aggregates, on the other hand, do not indicate any variation due to aggregate type. It should be noted that in Fig. 2b the strength of granite concrete at 28 days is lower than the 7-day value. This is primarily a variation which resulted from the local damage of capping that subsequently caused the overall failure of the test specimen.

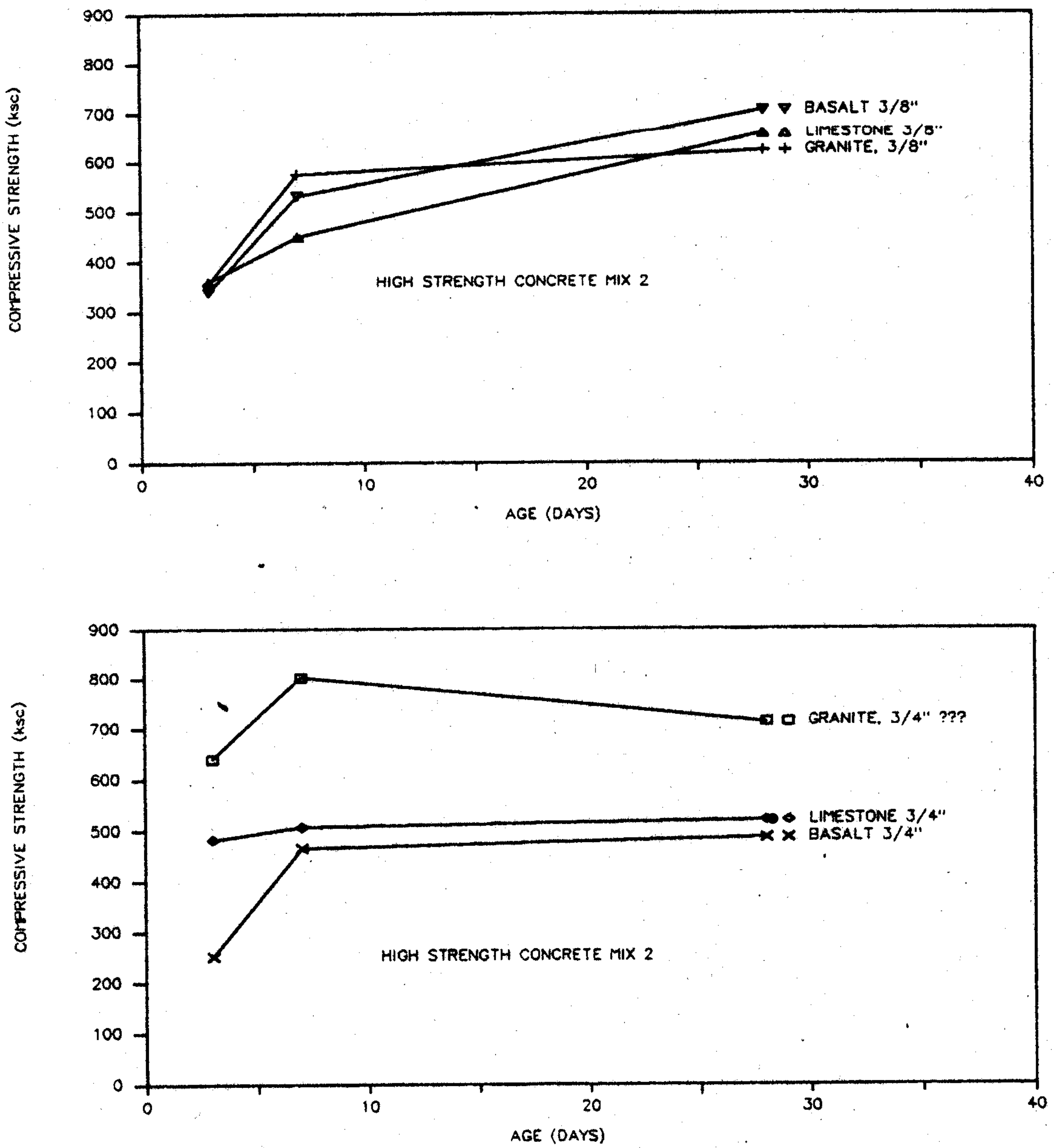
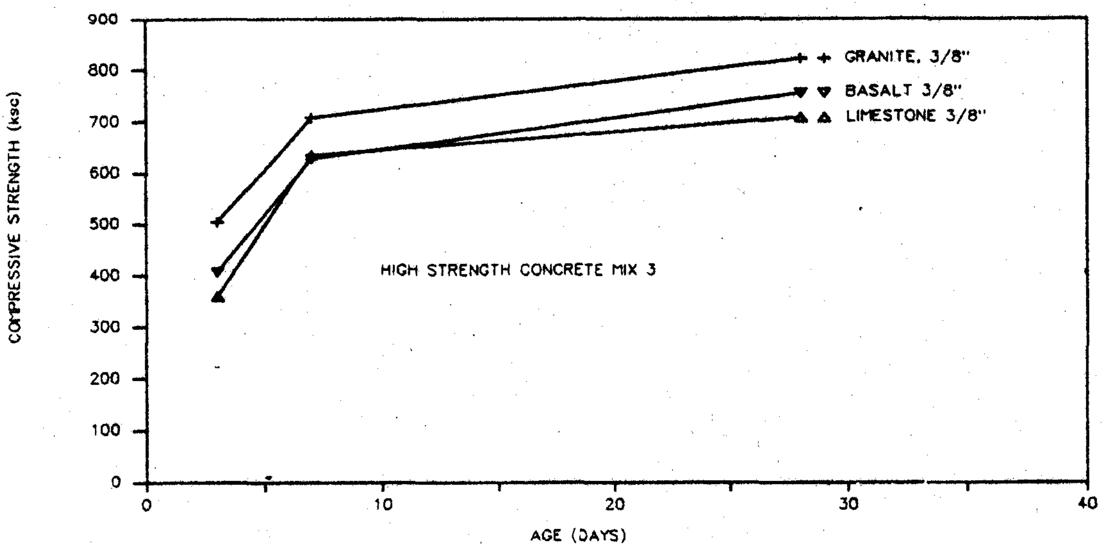


Fig. 2 Strength Development of Mix II High Strength Concrete with 10% (Powder) Microsilica

The strength of concrete obtained with the addition of 12% microsilica is in the range of 700 to 850 ksc which is roughly about 200 ksc (20 to 40% increase) stronger than the one with 10% microsilica. Occasionally, the capping failure caused a lower concrete strength at 28 days (data designated with ???). In general, the strength at 7 days represents the strength development of up to 85% of the ultimate compressive strength of the concrete. Rapid strength gained during the first 7 days of high strength concrete as shown in Fig. 3 and 4 can be quite beneficial to the overall cost saving of the construction project. Obviously, engineers and designers involved with any high strength concrete related construction need to clearly understand these performance so that proper adjustment of the construction process can be made. The design and construction practice that relies solely on the 28-day strength of concrete is certainly inadequate to take the advantage on these enhanced properties of concrete.



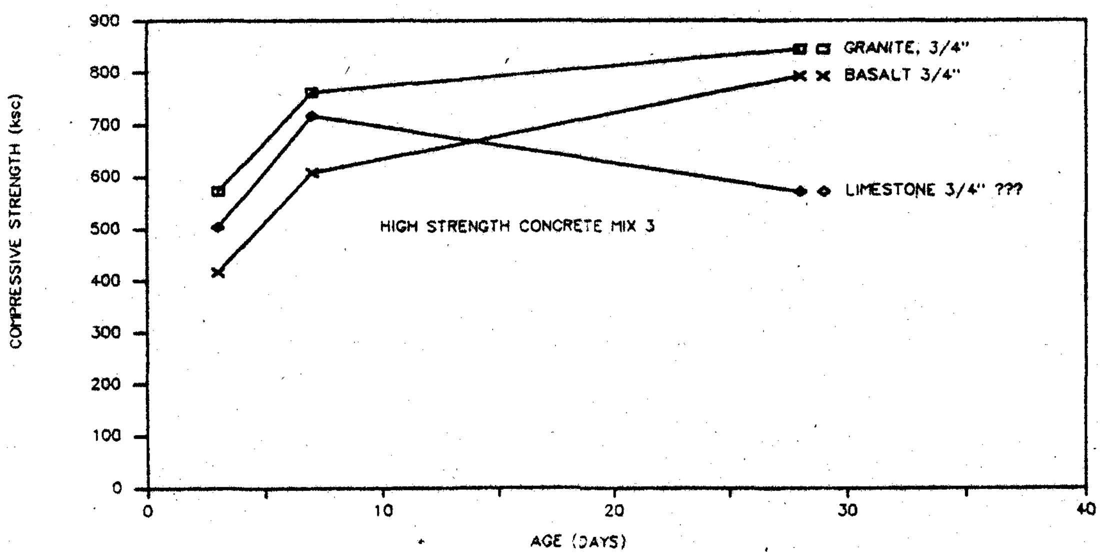
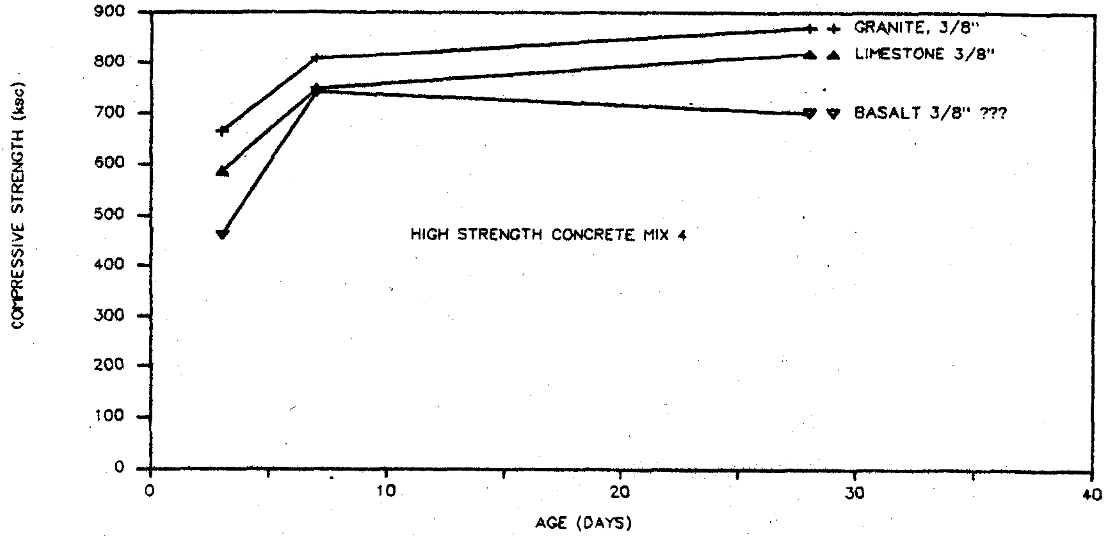


Fig. 3 Strength Development of Mix III High Strength Concrete with 12% (Powder) Microsilica



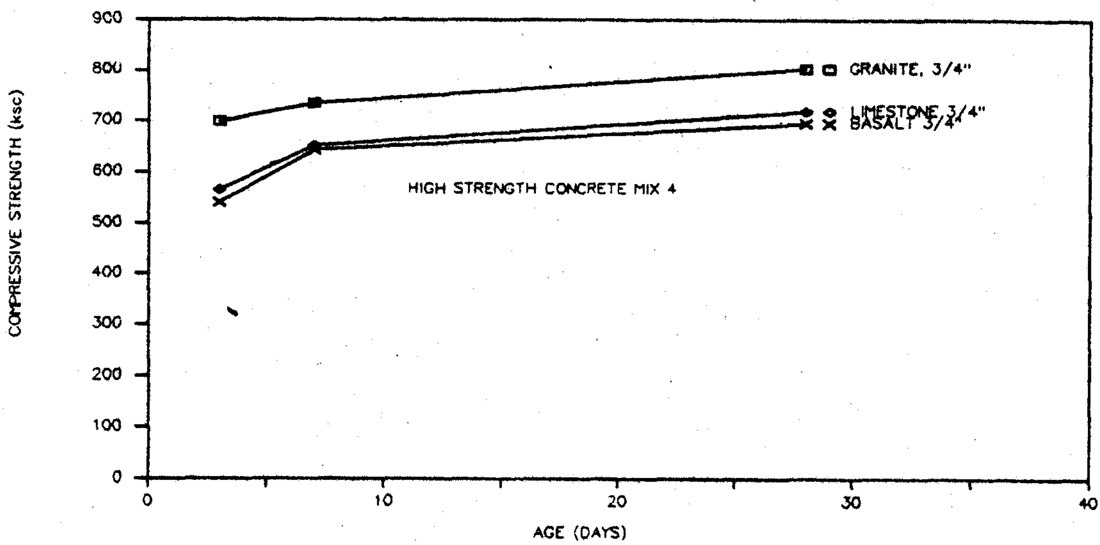


Fig. 4 Strength Development of Mix IV High Strength Concrete with 12% (Slurry) Microsilica

Effect of Aggregate Size

Aggregate size was reported to have influence on the strength of high strength concrete [6]. Fig. 5 compares the effect of aggregate size on the strength development of granite concrete. It can be seen that 3/4" aggregate performs better than 3/8" aggregate both in normal strength concrete as well as in high strength concrete matrices. The differences in both cases are about 14%. Fig. 6 shows the effect of aggregate size of basalt on high strength concrete. Hardly any difference was observed between the 3/4" and 3/8" aggregates. However, for limestone aggregate shown in Fig. 7, the aggregate size effect is quite significant. The 3/8" limestone gives a 14% higher strength than the 3/4" aggregate. The question on which size of aggregate will be more suitable for the development of high strength concrete may not have a simple answer since there are many factors affecting the strength of the cement-based composites. The major factor is probably the bond strength of the aggregate-matrix interface. The interfacial bond strength depends not only on the size of aggregate but also the type of aggregate. Limestone which is rich in calcium oxide and calcium carbonate may be more reactive to microsilica and cement paste than basalt. Depending on the strength of the matrix, the size of aggregate may have different role. If the matrix is stronger than the aggregate such as in the case of limestone, the size effect is more pronounced. This is because the weak aggregate will behave as a weak link to the system. As a result, the larger the particle, the weaker the overall system becomes. On the other hand, if the aggregate is stronger than the matrix such as in the case of basalt and granite, the presence of aggregate strengthens the cement composites. Therefore, the effect of aggregate size may not have a clear influence as in the case of basalt.

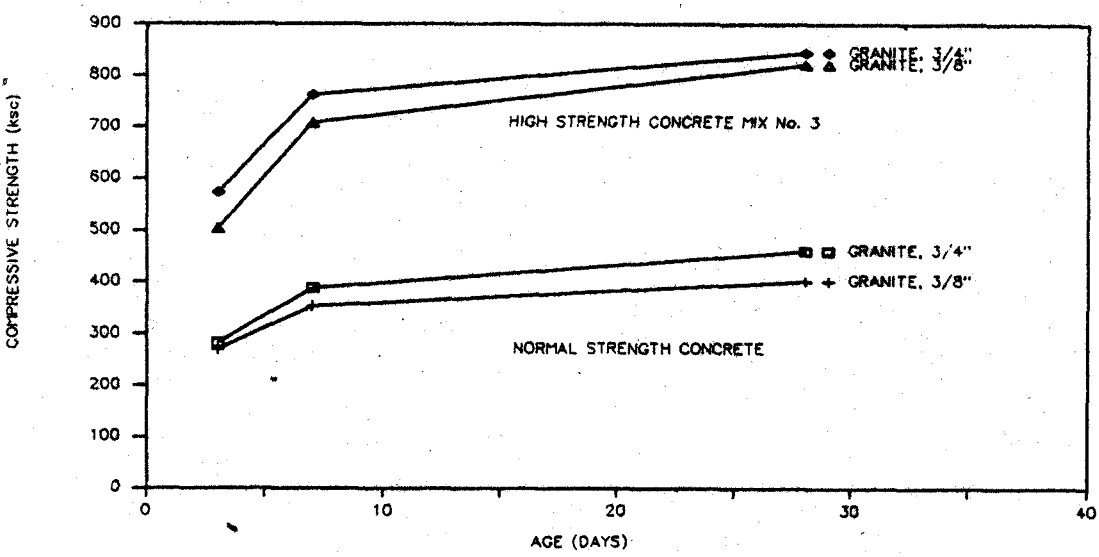


Fig. 5 Effect of Aggregate Size on the Strength of Granite Concrete

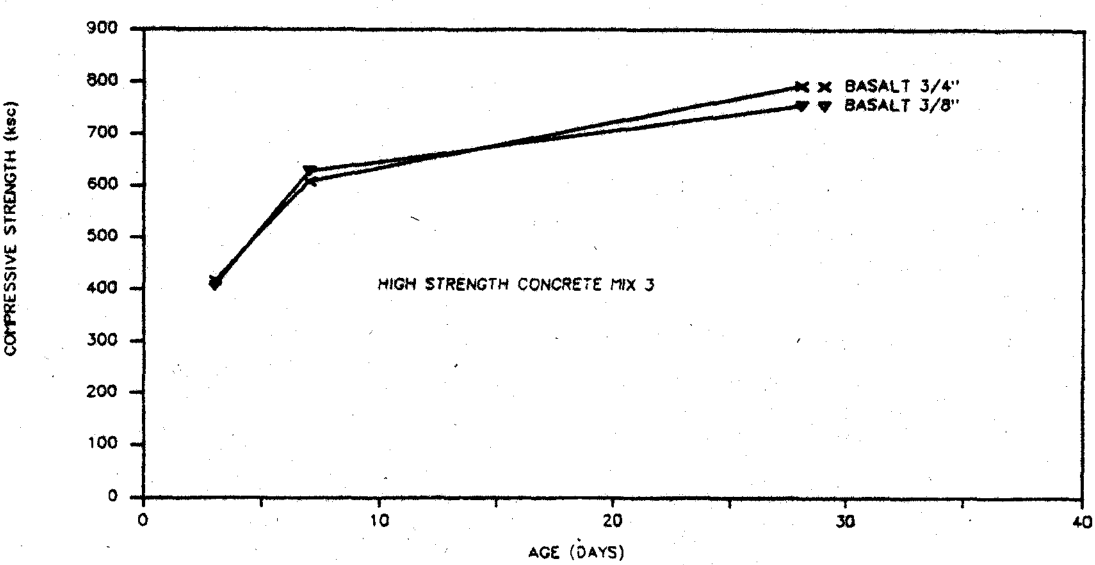
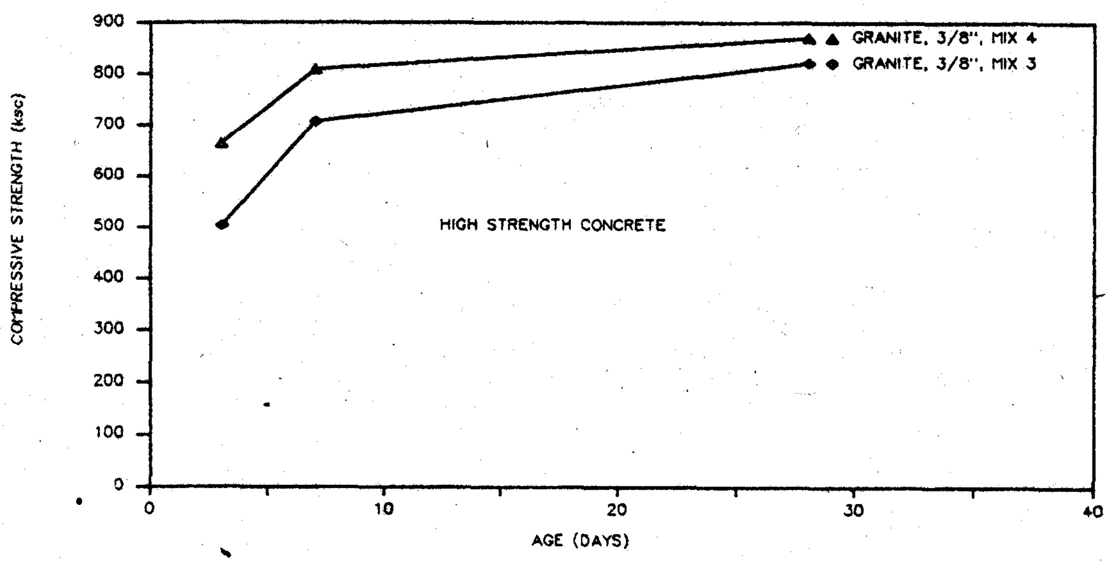


Fig. 6 Effect of Aggregate Size on the Strength of Basalt Concrete

that any local defect in the specimen will occur. Table IV summarizes the test results of high strength concrete using three different sizes of test cylinders, 3"x 6", 4"x 8", and 6"x 12". Although some variation exists, a general trend indicates that the larger test cylinder provides a more reliable test results. The 4"x 8" cylinder provides a very consistent test results and may be used as a smaller standard test specimen than the 6"x 12" cylinder. One major advantage for this selection is probably that the applied load is lower and the energy released at failure will not cause any damage to the testing machine. To thoroughly understand the size effect on the properties of concrete, one needs to consider the fracture behavior of concrete using the concept of fracture mechanics. For the sake of brevity, these will not be discussed here.



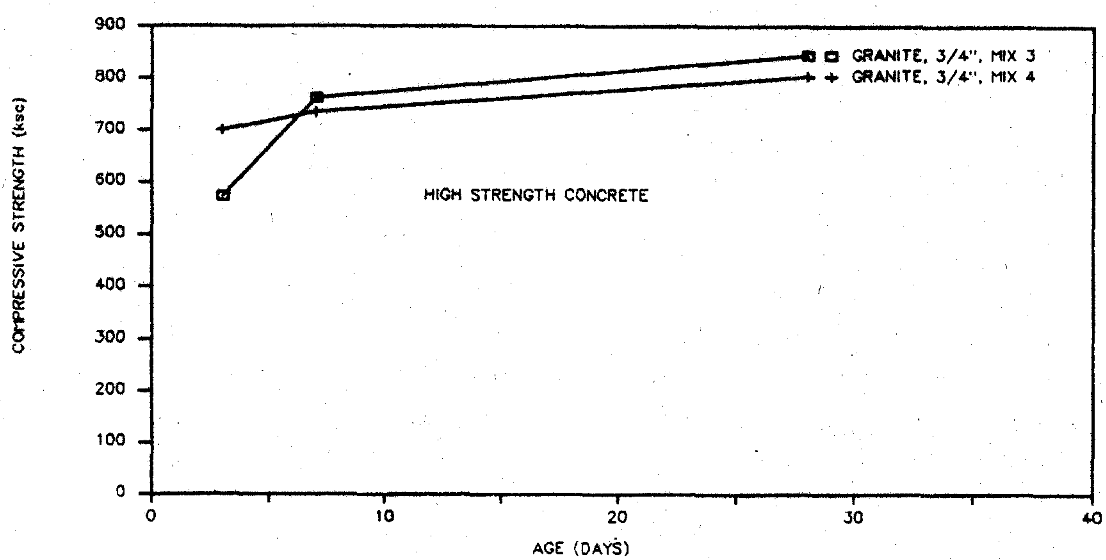


Fig. 8 Effect of Microsilica on High Strength Concrete

Table IV Compression of High Strength Concrete with Different Size of Samples

Mix No.	Agg. Size	Compressive Strength at 28 Days (ksc)								
		Granite Cylinder (in.)			Limestone Cylinder (in.)			Basalt Cylinder (in.)		
		3x6	4x8	6x12	3x6	4x8	6x12	3x6	4x8	6x12
3	3/4"	657	823	845	517	617	572	455	549	793
4	3/4"	701	738	804	710	788	719	476	745	696
3	3/8"	905	794	821	520	509	707	717	750	755
4	3/8"	773	891	871	733	916	820	628	716	702

Effect of Spiral Reinforcement

To enhance the brittle behavior of high strength concrete, lateral reinforcement is often provided. The presence of lateral reinforcement in concrete in many instances alters the mechanical properties of the cement matrices. In this study, four different spirals were cast in the high strength concrete specimens and were tested for its strength improvement. Table V summarizes the test results obtained from providing different amount of lateral reinforcement to the high strength matrices. It is interesting to note that, in general, specimens with no spiral reinforcement perform better than those with lateral reinforcement. The failure behavior of the tested sample shows that at peak load the energy released from only the cover leaving only the reinforced core to further sustain the applied load. For unreinforced cylinders, the energy released from the whole specimen and the failure results to a total collapse of the specimen. The influence of spiral reinforcement do not improve the ultimate load of the non-reinforced high strength matrix. However, a closer pitch of spiral provides a stronger reinforced core and therefore results to a higher post-cracking load carrying capacity. Fig. 9 shows the effect of spiral reinforcement on high strength concrete tested at the New Jersey Institute of Technology [7]. The results indicated that lateral reinforcement provided by steel hoop at a pitch distance of 1, 2, and 3 inches significantly enhanced the post-cracking or ductility of the high strength concrete. The closer the hoop reinforcement, the more ductile the concrete becomes. Unfortunately, under the existing testing facilities available at KMITT or at most concrete laboratories in Thailand, there are no modern testing machines which can be used to obtain such type of test results.

Table V Compression of High Strength Concrete with Different Spiral Pitch

Mix No.	Aggregate Type	Compressive Strength at 28 Days (ksc) Spiral Pitch (in.) 2	3	4	5	No Spiral
3	G 3/4"	821	787	543	679	845
3	L 3/4"	625	560	512	580	538
3	B 3/4"	536	496	575	606	625
4	G 3/4"	722	509	750	770	804
4	L 3/4"	622	572	537	628	719
4	B 3/4"	690	639	681	715	696
3	G 3/8"	679	699	662	656	821
3	L 3/8"	753	770	580	573	707
3	B 3/8"	787	780	650	625	787
4	G 3/8"	786	945	917	858	871
4	L 3/8"	920	917	637	594	820
4	B 3/8"	713	761	719	707	702

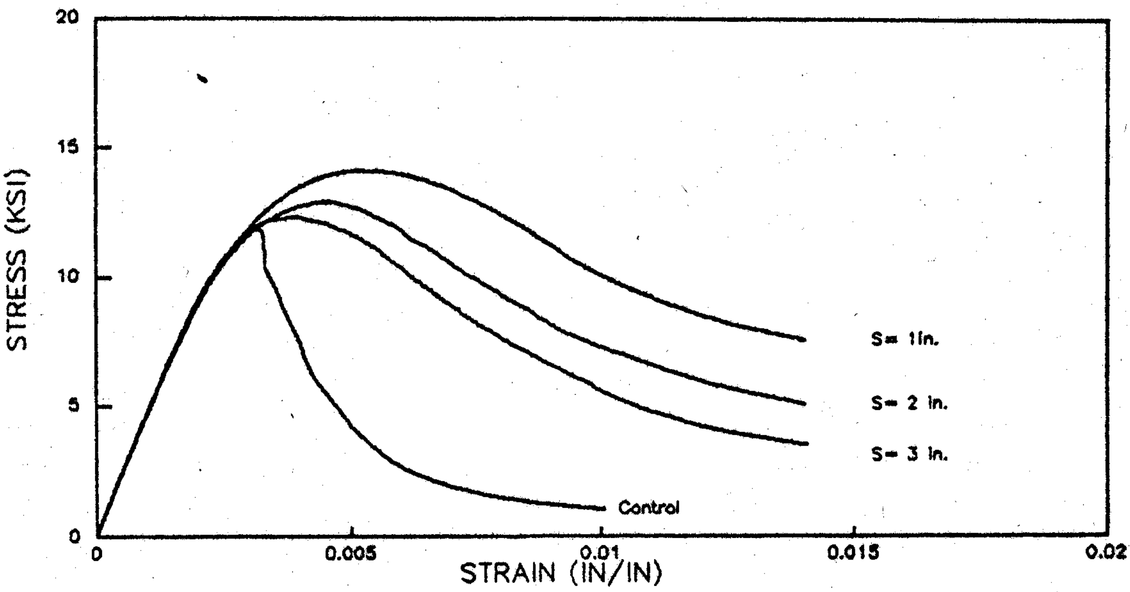


Fig. 9 Effect of Lateral Reinforcement on High Strength Concrete

CONCLUSIONS

From this investigation, the following conclusions can be drawn:

1. Coarse aggregate plays a crucial in the strength development of high strength concrete. Granite provides the strongest concrete as compared to limestone and basalt.

2. The size of aggregate has certain degree of influence on the strength of concrete. For granite aggregate, 3/4" aggregate gives higher strength concrete than the 3/8" aggregate. On the contrary, for limestone concrete, 3/8" aggregate performs better than 3/4" one.

3. Capping defects have a strong influence on the measured compressive strength of high strength concrete.

4. Slurry type of microsilica seems to produce higher strength concrete than the dry powder type one.

5. The size of test cylinder also affects the observed strength of high strength concrete. The larger size of test cylinder (4"x 8" and 6"x 12") gives more reliable result than the 3"x 6" cylinder.

6. Lateral reinforcement does not enhance the ultimate compressive strength of the high strength concrete. However, the presence of lateral reinforcement significantly improves the ductility of the high strength cement composites.

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