II–19. Strength and Deformation Characteristics of Masonry with Fiber Reinforced Mortar Joints

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ABSTRACT

Failure of masonry loaded in compression is initiated by differences in lateral strains between bricks and mortar joints. When loaded beyond its uniaxial compressive strength the lateral strains of the mortar exceed those of the bricks and lateral tensile strains are generated in the bricks which reduce the load carrying capacity of the masonry. Consequently, a reduction of lateral mortar strain should lead to a strength increase of the masonry. This may be achieved by the addition of short fibers to the mortar.

In an experimental study the validity of this hypothesis has been investigated. CEM-FIL glass fibers of various lengths and amounts have been added to ten types of mortar. Small masonry units have been made of five types of bricks. Compressive strength and longitudinal and lateral strains have been observed. In some instances the expected strength increase has been observed so that the compressive strength of the masonry approached that of the bricks. However, it is difficult to ascertain sufficient workability of the mortar, so that in some cases the strength of the masonry was decreased rather than increased by the addition of fibers. Presently, the composition of the mortar is optimized in order to achieve a reliable strengthening effect.

La maçonnerie sous pression externe est le plus souvent détruite à la suite de déformations transversales différentes de la pierre et du mortier. Sous l'teffet de tensions critiques, les déformations transversales du mortier surpassent celles de la pierre. Il en résulte la formation de fissures qui diminuent la résistance de la maçonnerie. Une réduction de la déformation transversale du mortier devrait en principe engendrer une résistance plus élevée de la maçonnerie. Il serait possible d'atteindre ce but en armant le mortier de fibres courtes.

On a examiné cette hypothèse au cours d'une étude expérimentale en mélangeant dix mortiers différents avec des fibres de verre CEM-FIL de longueur et quantités différentes. On détermina ainsi la résistance et les déformations longitudinales et transversales sur des petits échantillons de 5 pierres attenantes.

Quelques cas manifestaient une augmentation de la résistance si bien que la résistance de la maçonnerie équivalait presque celle des briques. La difficulté résidait pourtant dans la production de mortiers aux fibres de verre bien maniables si bien que dans certains cas la résistance de la maçonnerie diminuait à mesure que le contenu de fibres augmentait. Il fut possible néanmoins d'obtenir une ductilité améliorée de la maçonnerie en tenant compte de l'augmentation du contenu des fibres. Au cours d'expériences plus récentes l'on parvint à fabriquer des mortiers de fibres bien maniables permettant d'améliorer la résistance de la maçonnerie.

Druckbelastetes Mauerwerk geht meist durch unterschiedliches Querdehnungsverhalten von Stein und Mörtel zu Bruch. Bei Spannungen oberhalb der einachsigen Mörteldruckfestigkeit übersteigen die Querdehungen des Mörtels jene der Steine, so daß im Stein Risse entstehen, die die Mauerwerksfestigkeit reduzieren. Deshalb müßte eine Behinderung der Querdehnung des Mörtels zu einer erhöhten Mauerwerksdruckfestigkeit führen. Dies könnte durch eine Bewehrung des Fugenmörtels mit kurzen Fasern erreicht werden.

In einer experimentellen Arbeit wurde diese Hypothese untersucht. Zehn verschiedenen Mörteln wurden CEM-FIL Glasfasern verschiedener Länge und in verschiedener Menge zugegeben. An kleinen Mauerpfeilern aus 5 aneinanderliegenden Steinen wurde die Druckfestigkeit sowie das Längs- und Querdehnverhalten bestimmt.

In einigen Fällen konnte eine Festigkeitssteigerung beobachtet werden, so daß die Mauerwerksfestigkeit nahe der Steinfestigkeit lag. Es war jedoch schwierig, gut verarbeitbare Glasfasermörtel herzustellen, so daß in einigen Fällen die Mauerwerksfestigkeit mit zunehmendem Fasergehalt abnahm. Eine deutlich verbesserte Duktilität des Mauerwerks mit zunehmendem Fasergehalt konnte jedoch in allen Fällen erreicht werden. In neueren Versuchen konnten jedoch gut verarbeitbare Fasermörtel hergestellt werden, mit denen eine Verbesserung der Mauerwerksdruckfestigkeit möglich ist.

Le murature sollecitate a pressione si rompono per effetto di dilatazioni trasversali differenti dei mattoni e della malta. In presenza di tensioni al di sopra della resistenza alla pressione monoassiale della malta, le dilatazioni trasversali della malta sono maggiori di quelle dei mattoni in modo che si producono delle fessure nella muratura riducendo cosâı la resistenza dei mattoni. Perciò evitando la dilatazione trasversale della malta si dovrebbe arrivare a una resistenza maggiore per la muratura. Ciò si potrebbe ottenere mediante una armatura della malta delle giunture con fibre corte.

E' stata esaminata questa ipotesi in un lavoro sperimentale. A dieci differenti malte sono state aggiunte delle fibre di vetro CEM-FIL con una lunghezza differente e in quantità variabile. Su piccoli pilastri di muratura, formati da cinque mattoni sovrapposti, è stata determinata la resistenza alla pressione e cosaî pure il comportamento delle dilatazioni longitudinali e trasversali.

In alcuni casi è stato osservato un incremento della resistenza, cosicchè la resistenza della muratura era quasi uguale a quella dei mattoni. Era stato però difficile fabbricare delle malte di fibre di vetro ben elaborate, cosicchè in alcuni casi la resistenza della muratura aveva presentato invece una diminuizione al crescere del tenore di fibre. Ciononostante in tutti casi è stato possibile una duttilità notevolmente migliore al crescere della percentuale di fibre. Nelle ricerche più recenti abbiamo potuto però fabbricare malte di fibre che si lasciano elaborare bene. Con queste è stato possibile ottenere un miglioramento nella resistenza a pressione della muratura.

INTRODUCTION

It is a generally accepted hypothesis that brick masonry loaded in compression fails at stresses considerably below the compressive strength of the bricks because of differences in lateral strains of the bricks and of the bed joint mortar. In most instances the lateral strains of the joints exceed those of the bricks. Thus a triaxial state of stress—longitudinal compression and biaxial lateral tension—is developed in the bricks. Because of the comparatively low tensile strength of the bricks, masonry fails after several vertical cracks have developed in the bricks[1].

From this failure mechanism of masonry loaded in compression it follows that restraint of lateral mortar strains should strengthen masonry loaded in compression. Such restraint may be provided by lateral reinforcement of the joint mortar. For reasons of economy and handling it appeared to be particularly promising to use short fibers mixed with the fresh mortar rather than conventional steel reinforcement. The advantages of fiber reinforcement in a brittle cementitious matrix have been demonstrated during recent years in numerous investigations[2].

The objective of the investigation described in the following was to study the feasibility of using fiber-reinforced mortar joints for masonry units, to develop suitable fiber-reinforced mortars and to determine strength and deformation properties of simple, fiber-reinforced masonry units.

DEVELOPMENT OF FIBER-REINFORCED MASONRY MORTARS

Test Program

The principal difficulty in developing suitable fiber-reinforced masonry mortars is the achievement of sufficient workability of the mortars.

In some preliminary experiments it had been found that among the commercially available fibers, glass fibers are the most suitable from the view point of workability. Because of their improved durability in an alkaline environment CEM-FIL fibers have been used in subsequent studies[3].

For the tests two fiber lengths, 12 mm and 24 mm with fiber concentrations of 0; 1; 1.5 and 2 percent by volume have been chosen. Higher percentages would lead to uneconomical mortars of insufficient workability.

The types of sand investigated have been a Rhine river sand (sand A) with a maximum size of 1 mm and crushed sand (sand B) with a maximum size of 2 mm. Hydrated white lime, hydraulic lime and portland cement PZ 35 and PZ 55 with a specific surface of 3900 and of 4990 cm^2/g, respectively, have been used. In addition, two types of water reducers as well as fly ash have been employed to improve workability of the fresh mortars.

Three types of mortar have been investigated:

type I : lime-cement mortar
type II : hydraulic lime-cement mortar
type III : portland cement mortar

The principal parameters which have been varied for each type of mortar are:

fiber length and fiber content;
mix proportions and water content;
amount of water reducers;
fly ash content;
type, maximum size and gradation of sand.

Compressive strength and flexural strength have been determined on prisms 40×40×160 mm in accordance with the German specification DIN 1164 (4). Workability and water retention have been evaluated by visual inspection, since the standard tests methods for conventional mortars could not be applied successfully to fiber mortars.

Experimental Results

Further preliminay tests had shown that for fiber mortars with sufficient workability the sand content has to be reduced to approx. one half of the sand content of conventional mortars. Even with a reduced sand content the water content of the fiber mortars had to be increased because of the large water demand of the fibers. The workability of the mortars could be enhanced by the addition of water reducers, and in the case of type III mortars by the addition of fly ash.

Following the preliminary tests 10 different mixes of mortar of type I, II and III with 12 mm and 24 mm fibers and a fiber content of 2 percent by volume have been designed and tested with regard to workability and water retention. From these tests two mixes have been chosen for each type of mortar for subsequent strength tests. In Table 1 the composition of these mortars Type I and II are given. In Table 2 compressive and flexural strength as well as failure strain under compression of the mortars type I and III are summarized. The studies of mortars type II are still under way and will be reported at some later time.

For the lime-cement mortars the water cement-ratio could be kept constant for all mixes by the addition of water reducing agents (Table 1). For the cement mortars the addition of fly ash and a water reducing agent have not been sufficient to maintain suitable workability of the fiber mortars. Consequently, the water-cement ratio had to be increased with increasing fiber content.

According to Table 2 the addition of fibres resulted in a substantial increase of compressive strength, flexural strength and failure strain with the exception of some of the type III mortars. In these cases the effect of fiber reinforcement was partially offset by reduced workability and an increase of the water-cement ratio.

TESTS ON MASONRY UNITS

Test Program

In order to study the strength characteristics of fiber-reinforced masonry simple masonry units as shown in Fig. 1 have been manufactured. They consisted of five bricks and four fiber-reinforced mortar joints, 12 mm thick. The loaded ends of the specimens have been capped with high strength mortar. Both longitudinal and lateral strains in one mortar joint and on both sides of one brick have been measured. The specimens have been loaded in concentric compression at a constant strain rate of approx. 1mm/m, min.

For the experiments four types of clay bricks have been used. The brick characteristics are summarized in Table 3.

The mortar characteristics have been discussed in an earlier section and in Tables 1 and 2. The following combinations of bricks and types of mortar have been used for the masonry units:

	Mortar type I	Mortar type II	Mortar type III
Brick A	x	x	
Brick B		x	x
Brick C	x		
Brick D		x	x

Five specimens have been tested and manufactured for each combination. The tests with the type II mortars are still in progress. They will be reported at some later date.

Test Results

Strength Data

In Table 4 the results of the compressive strength tests are given as far as available at this time. Each strength value is the average of five individual values. For the combination brick A/lime-cement mortar type I a strength increase up to 28 percent of the strength of plain mortar specimen has been obtained. Similar values have been observed for bricks B/mortar type I. Masonry units made of bricks type C and D have been tested only with portland cement mortars resulting in a strength increase up to 12 percent for masonry with type C bricks and no significant increase for masonry with type D bricks.

There has been no decisive effect of fiber length. Particularly for the type I mortars the compressive strength of the masonry units increases with increasing fiber content.

Stress-Strain Relationships

In Figs. 2 and 4 through 7 stress-longitudinal strain relationships are given for the masonry units made of various combinations of bricks and fiber mortars. Fig. 3 shows the stress-lateral strain relationships for masonry units made of Brick A and mortar type I.

In Table 5 the longitudinal strains at maximum stress are summarized.

The stress-strain relationships clearly show that the fiber reinforcement of the mortars resulted in a substantial increase of ductility of the masonry units. The specimens with plain mortars showed brittle behavior with a sudden explosion type failure at maximum stress, whereas the specimens with fiber mortars failed gradually and showed a well developed descending portion of the stress strain diagram. The same tendency can be seen from the failure strains given in Table 5: for the mortar type I specimens an increase in failure strain by factors up to 2.2 has been observed. For the mortar type III specimens increase by factors up to 2.0 have been recorded.

SUMMARY AND CONCLUSIONS

Glass fiber reinforced mortars with sufficient workability may be produced by the reduction of sand content and addition of water reducing admixtures and of fly ash to conventional masonry mortars. For the portland cement mortars also the water-cement ratio has to be increased up to 15 percent. Furthermore, the fiber content should not exceed approx. 2 percent by volume.

Glass fiber reinforcement resulted in an increase of compressive strength and of flexural strength of the lime-cement mortars up to 28 percent and of 110 percent, respectively. This strength increase was considerably less for the portland cement mortars because of the required increase of the water-cement ratio of such mortars with increasing fiber content.

The improved strength characteristics of the fiber reinforced mortars have been accompanied by an increase of failure strains under compression by factors of up to 3.5 for the lime-cement mortars and up to 1.9 for the portland cement mortars. Tests in which the lateral strains of the fiber mortars are being measured are still under way.

Glass fiber reinforcement of the mortars resulted in a strength increase of masonry up to 30 percent of the strength of masonry units with conventional lime-cement mortar. Since a similar strength increase may be obtained by using a conventional mortar of higher strength, this strength increase cannot be considered to be of particular economic significance.

The strength increase provided by fiber reinforcement is even less for portland cement mortars.

These results do not necessarily contradict the initial working hypothesis given in an earlier section of this paper: particularly for the portland cement mortars the water-cement ratios had to be increased compared to the water-cement ratio of the plain mortars. Thus the quality of the mortar matrix decreases and partially offsets the positive effects of fiber reinforcement. More important, the mortar tests described in an earlier section show clearly that the increase

of mortar strength by fiber reinforcement is accompanied by an even larger increase of failure strain. This will lead to increased lateral strains and biaxial lateral tensile stresses in the bricks of a masonry unit as can be seen from Fig. 3.

The advantage of fiber reinforced mortars for masonry clearly is the enhanced ductility of the masonry. The explosive type failure which is typical particularly for high strength masonry, did not take place in fiber reinforced masonry units. The stress-strain relatinships of the fiber reinforced mortars show a comparatively flat descending portion. Even at compressive strains of 1 percent the masonry units may sustain stresses of one half of their ultimate compressive strength or more.

Fiber reinforced mortars are believed to enhance the ductility of masonry units by restraining lateral strains in the bricks after the maximum load has been reached, thus preventing the rapid opening of vertical cracks in the bricks.

The investigation reported herein is being continued. Different types of mortar and of fibers will be investigated which are more effective in providing restraint of lateral strains of bricks and of mortar. Particular emphasis will be placed on the post-failure behavior of such materials.

REFERENCES

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TABLE 1—Composition of Mortars

Series	Type	Type of Sand	Mix Proportions by Volume: Cement	Lime	Hydraulic Lime	Fly Ash	Sand	Water Reducer: Type	Percent by Weight of Cement	Fibers: Length mm	Content Percent by Volume	Water/Cement by Weight
1	I	A	1	2	—	—	4	—	—	—	0	1,42
2								A	1,5	12	1	1,42
3								A	3,5	12	1,5	1,42
4								A	5,5	12	2,0	1,42
5								A	2,0	24	1,0	1,42
6								A	4,0	24	1,5	1,42
1	III	A+B	1	—	—	0,23	2	B	2,0	—	0	0,87
2										12	1	0,92
3										12	1,5	0,98
4										12	2	1,01
5										24	1,0	0,92
6										24	1,5	0,98

TABLE 2—Mechanical Properties of Mortars, Age 28 Days

Series	Mortar Type	Water/Cement by Weight	Fibers: Length mm	Content Percent by Volume	Compressive Strength N/mm²	Flexural Strength N/mm²	Failure Strain mm/m
1	I	1,42	—	0	12,8	3,3	3,7
2		1,42	12	1,0	13,4	3,5	5,2
3		1,42	12	1,5	14,9	4,1	7,8
4		1,42	12	2,0	16,1	6,1	8,5
5		1,42	24	1,0	14,8	5,0	11,4
6		1,42	24	1,5	16,8	6,9	12,8
1	III	0,87	—	0	36,4	5,7	4,0
2		0,92	12	1,0	40,0	7,0	7,0
3		0,98	12	1,5	40,8	7,9	7,1
4		1,01	12	2,0	39,3	8,0	7,7
5		0,92	24	1,0	36,6	8,1	6,4
6		0,98	24	1,5	36,4	8,8	6,5

TABLE 3—Characteristics of Clay Bricks

No.	Type of Brick	Dimensions, mm Length	Width	Height	Net Area / Cross Area	*Standard Compressive Strength N/mm²
A	vertically cored	232	110	70	0,52	21.6
B	solid	225	110	70	—	29.7
C	solid	242	118	71	—	37,6
D	vertically cored engineering brick	230	109	69	0,85	64,7

*Determined in accordance with DIN 105 (5)

TABLE 4—Compressive Strength of Masonry Units

Type of Brick	Fiber Length mm	Fiber Content Volume Percent	Mortar Type I: Compressive Strength N/mm²	Mortar Type I: Masonry Strength / Brick Strength	Mortar Type III: Compressive Strength N/mm²	Mortar Type III: Masonry Strength / Brick Strength
A	—	0	8,9	0,41		
	12	1,0	10,0	0,46		
	12	1,5	10,9	0,50		
	12	2,0	11,3	0,52		
	24	1,0	10,4	0,48		
	24	1,5	10,0	0,46		
B	—	0			28,6	0,96
	12	1,0			30,6	1,03
	12	1,5			31,1	1,05
	12	2,0			29,2	0,98
	24	1,0			31,7	1,07
	24	1,5			26,6	0,90
C	—	0	15,7	0,42		
	12	1,0	17,0	0,45		
	12	1,5	18,1	0,48		
	12	2,0	18,8	0,50		
	24	1,0	16,7	0,44		
	24	1,5	18,8	0,50		
D	—	0			43,4	0,67
	12	1,0			44,6	0,69
	12	1,5			41,6	0,64
	12	2,0			40,0	0,62
	24	1,0			41,3	0,64
	24	1,5			39,4	0,61

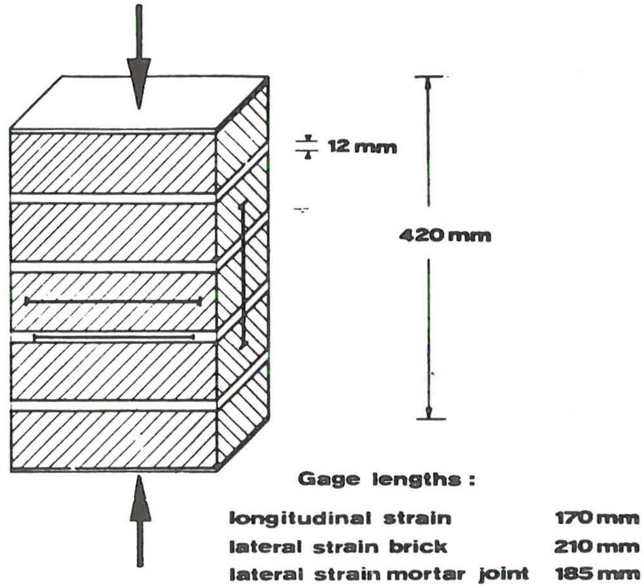

Figure 1. Test-Set Up and Specimen for Strength Tests on Masonry Units

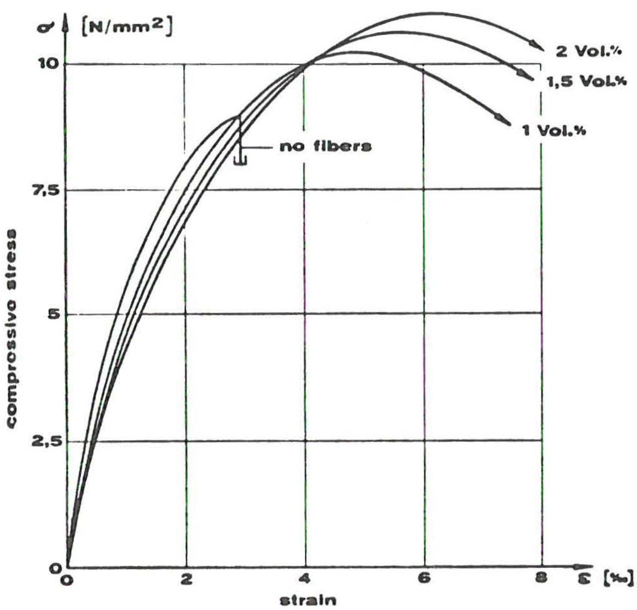

Figure 2. Stress—Strain Diagrams of Masonry Units. Brick : Type A; Mortar : Type I; Fiber length:12mm

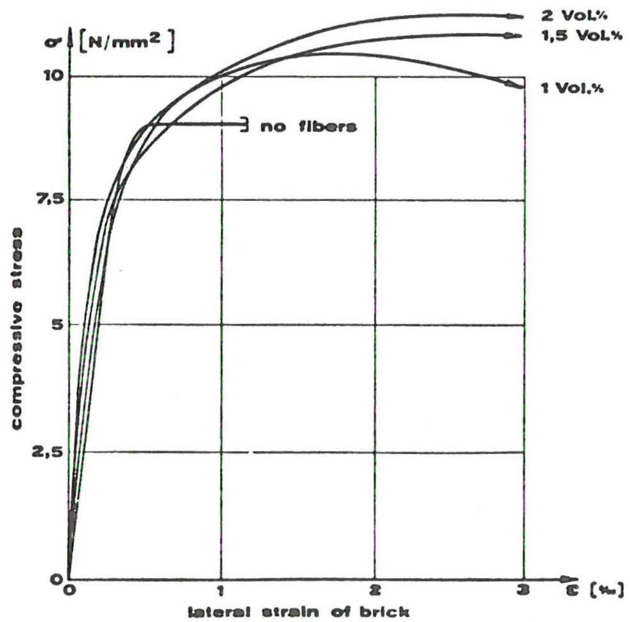

Figure 3. Stress—Lateral Strain Diagrams of Masonry Units
Brick : Type A; Mortar : Type I; Fiber length:12mm

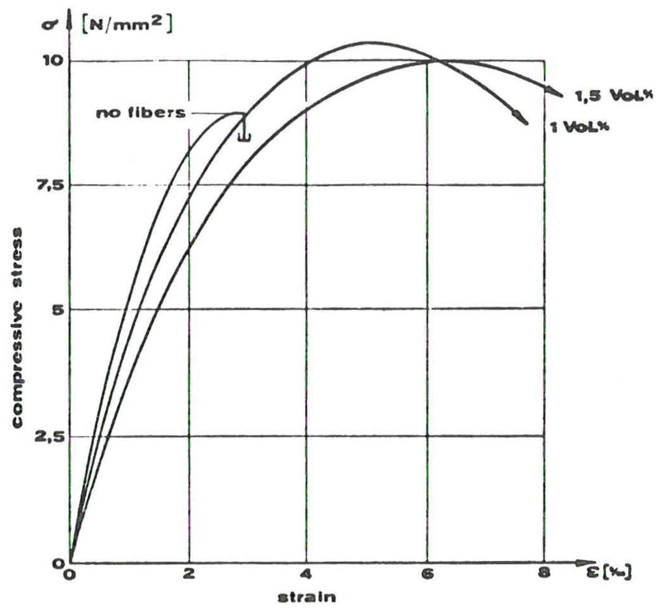

Figure 4. Stress—Strain Diagrams of Masonry Units
Brick : Type A; Mortar : Type I; Fiber length:24 mm

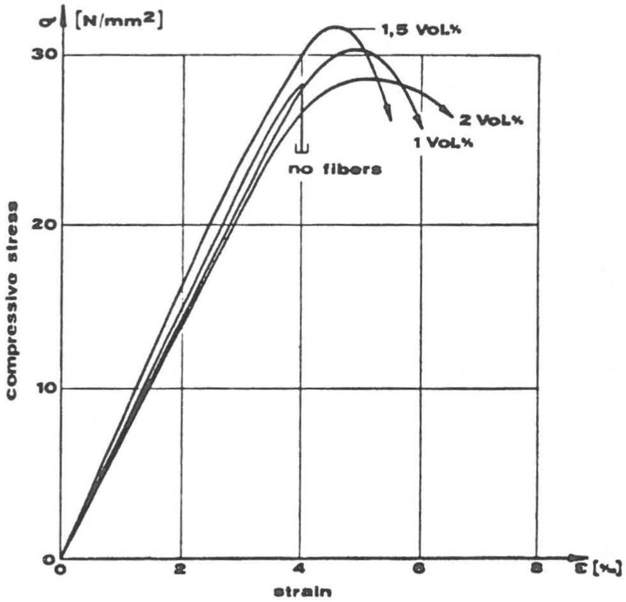

Figure 5. Stress—Strain Diagrams of Masonry Units Brick : Type B; Mortar : Type III; Fiber length:12 mm

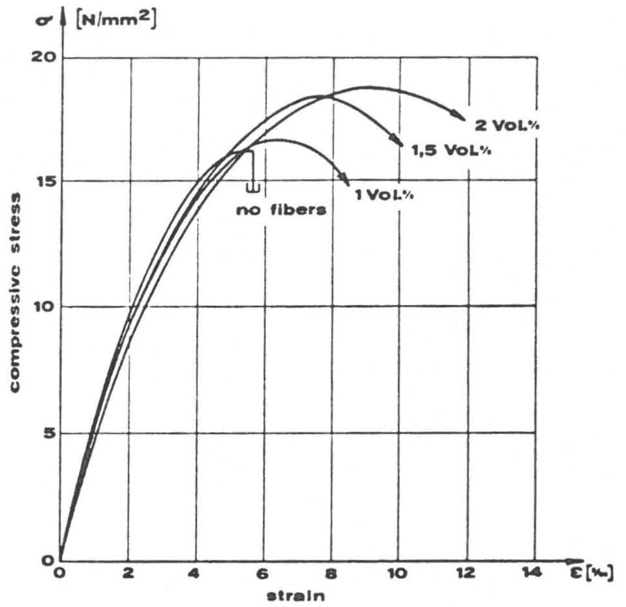

Figure 6. Stress—Strain Diagrams of Masonry Units Brick : Type C; Mortar : Type I; Fiber length:12 mm

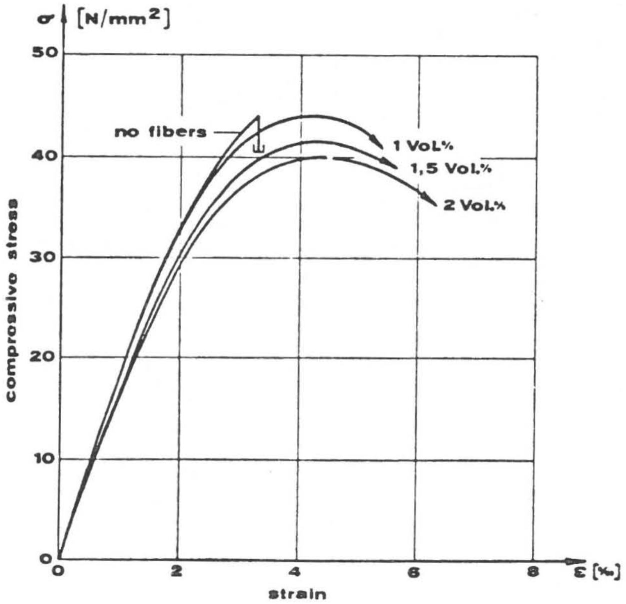

Figure 7. Stress—Strain Diagrams of Masonry Units Brick : Type D; Mortar : Type III; Fiber length:12 mm

TABLE 5—Longitudinal Failure Strains of Masonry Units

Type of Brick	Fiber Length mm	Fiber Content Percent	Failure Strain mm/m for Mortar	
			Type I	Type III
A	—	0	2,9	
	12	1,0	4,5	
	12	1,5	5,8	
	12	2,0	6,1	
	24	1,0	5,0	
	24	1,5	6,5	
B	—	0		4,0
	12	1,0		4,6
	12	1,5		4,4
	12	2,0		4,6
	24	1,0		4,7
	24	1,5		4,4
C	—	0	5,4	
	12	1,0	6,4	
	12	1,5	7,6	
	12	2,0	9,1	
	24	1,0	6,9	
	24	1,5	7,2	
D	—	0		3,4
	12	1,0		3,9
	12	1,5		4,0
	12	2,0		4,2
	24	1,0		5,8
	24	1,5		7,0