Analysis and consideration on results of long term mortar strength test*1

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Abstract

In this research, the strength of mortar specimens made during construction of Otaru port were analyzed. The experiment was planned and initiated by Dr. Isami HIROI in the 19th century.

The purpose of this study is to research the long-term strength and durability of mortar specimens. The results of these long-term experiments carried out with various internal factors (type of cement, type of fine aggregate, type of volcanic ash, water cement ratio) and external factors (age and exposure conditions such as in water, in air, and in sea water) are analyzed.

The long-term mortar strength test can be summarized as follows : ① tensile strength is affected by water-binder ratio, water-cement ratio, cement proportion, and volcanic ash proportion. ② the reliability of not declining the tensile strength of age 28 days was 52 %, that of 3 months ; 5 %, and that of 1 year ; nearly 0 % at the age 80 years.

1. Introduction

The purpose of this study is to research the long-term strength and durability of mortar specimens. The experiment was planned and initiated by Dr. Isami HIROI in the 19 the century. The results of these long-term experiments carried out with various internal factors (type of cement, type of fine aggregate, type of volcanic ash, water cement ratio) and external factors (age and exposure conditions such as in water, in air, and in sea water) are analyzed.

2. Method

In order to analyze long-term change, an exponential function model is developed to express increasing strength at age in a form with a peak. The model is well able to express changes in strength. In order to evaluate the reliability of long-term strength to taking into account variations and changes in strength, the reliability analysis model are applied.

In this research, the strength of mortar specimens when construction of Otaru port (Photo.-1) began were analysis.

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Reliable data up to 1991 were analyzed. To grasp effects on long-term strength, factors such as type of cement, type of volcanic ash, preserved conditions, and mortar mix proportion were studied taking moving average as property.

Procedure for making, curing, preserving and testing mortar specimens is shown in Fig. 1, Photo.-2, and Photo.-3. The types of cement, sand, and volcanic ash and their ratios are shown in Fig.2. There are 13 types of cement, 10 types of sand, and 15 types of volcanic ash. The two types of water used as mixing water were fresh water (from the in area of the construction site) and sea water (from in Otaru port).

The combination of typical mix proportion and water proportion are shown in Table 1. Specimen data suitable for analysis comprises 136 mix proportions. After curing for a fixed time, the specimen were preserved under 3 conditions: air, sea water, and fresh water.

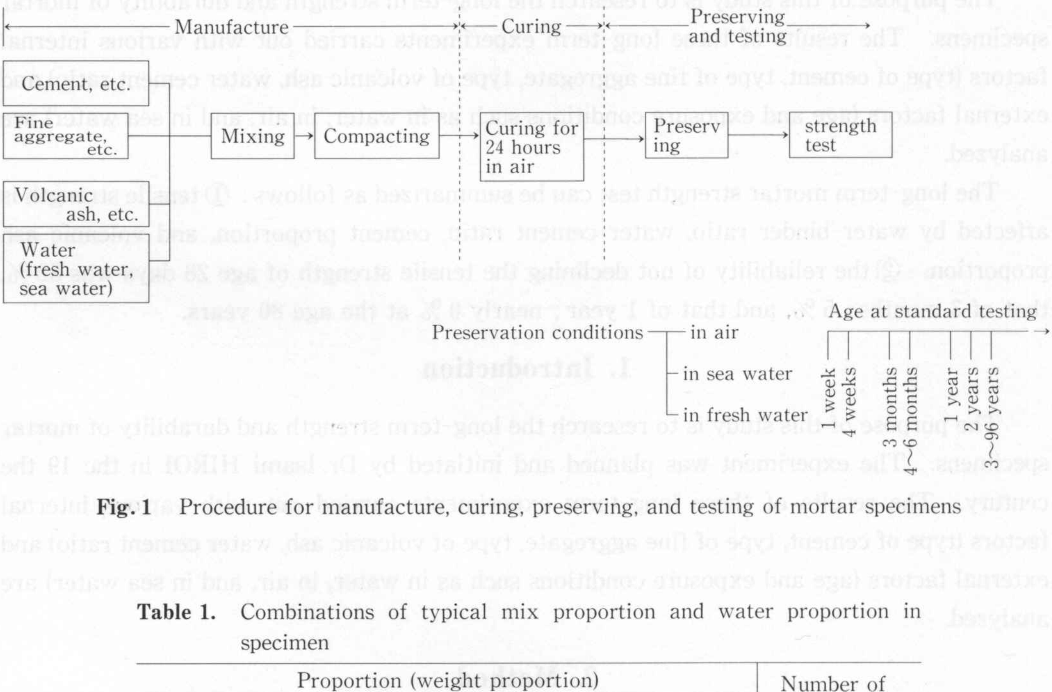


Fig. 1 Procedure for manufacture, curing, preserving, and testing of mortar specimens

Table 1. Combinations of typical mix proportion and water proportion in specimen

Proportion (weight proportion)				Number of combination
Cement	Volcanic ash	Sand	Water	
0.6	0.4	3	0.32~0.42	28
0.8	0.2	3	0.29~0.46	29
1.0	0	2	Not clear	17
1.0	0	3	0.20~0.44	117
1.0	0.5	3	0.28~0.50	53
1.0	1.0	3~4	0.11~0.46	42
1.0	1.0~2.0	5~6	0.05~0.42	32
Others except above				173
Total				491

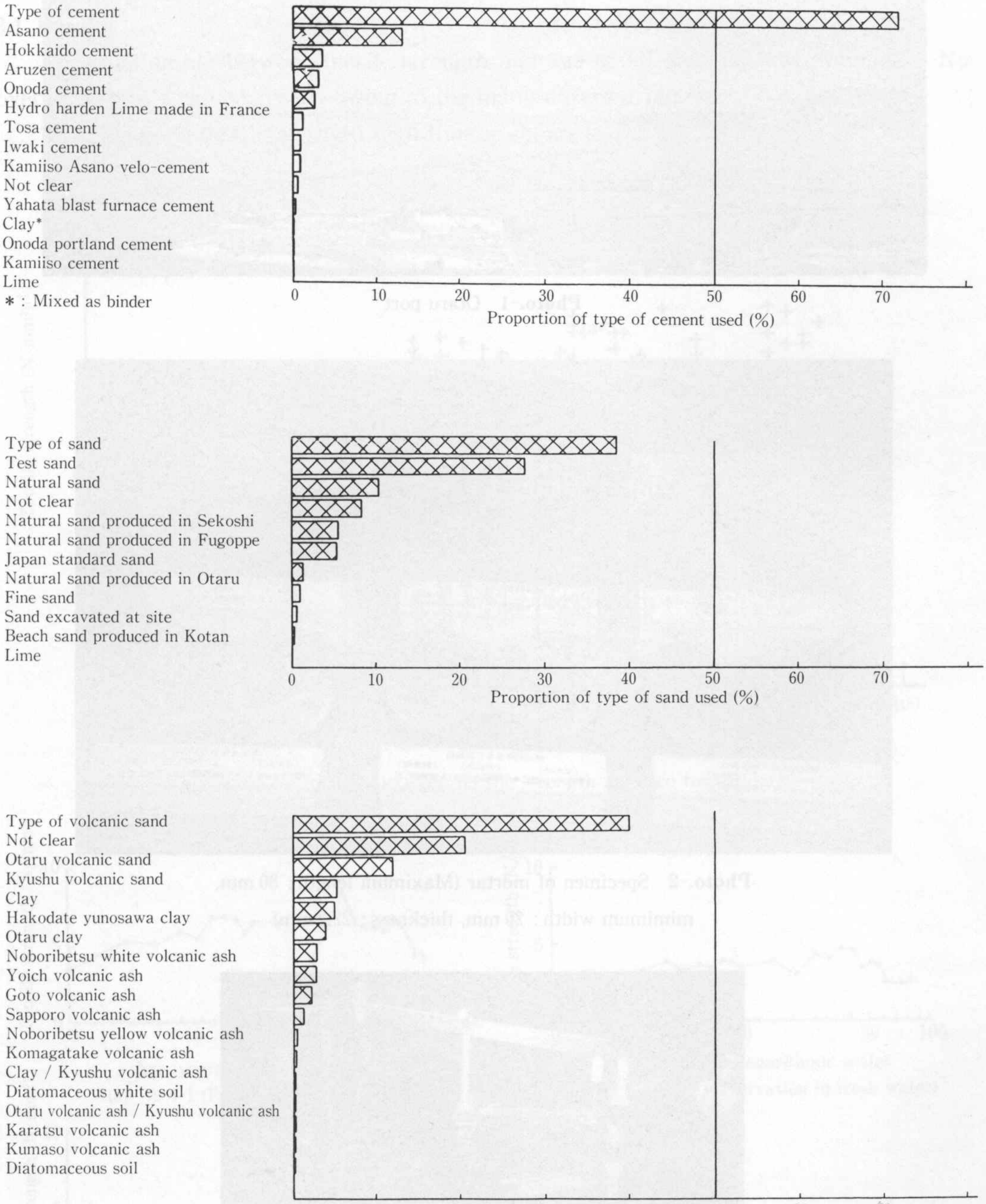


Fig. 2 Types of cement, sand, and volcanic ash used in specimen mixes

Photo.-1 Otaru port

Photo.-2 Specimen of mortar (Maximum length : 80 mm, mimimum width : 20 mm, thickness : 22.2 mm)

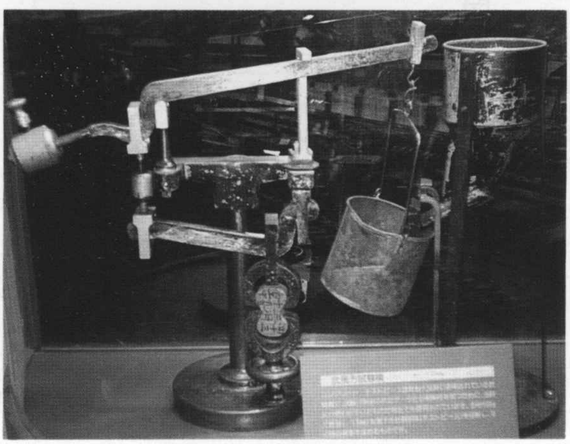


Photo.-3 Apparatus of tensile strength

3. Results and Consideration

3.1 Results

The relationship between tensile strength and age of all data is shown in Fig.3. No overall tendency can been seen owing to the many different factors.

The change in tensile strength with time is shown in Fig. 4.

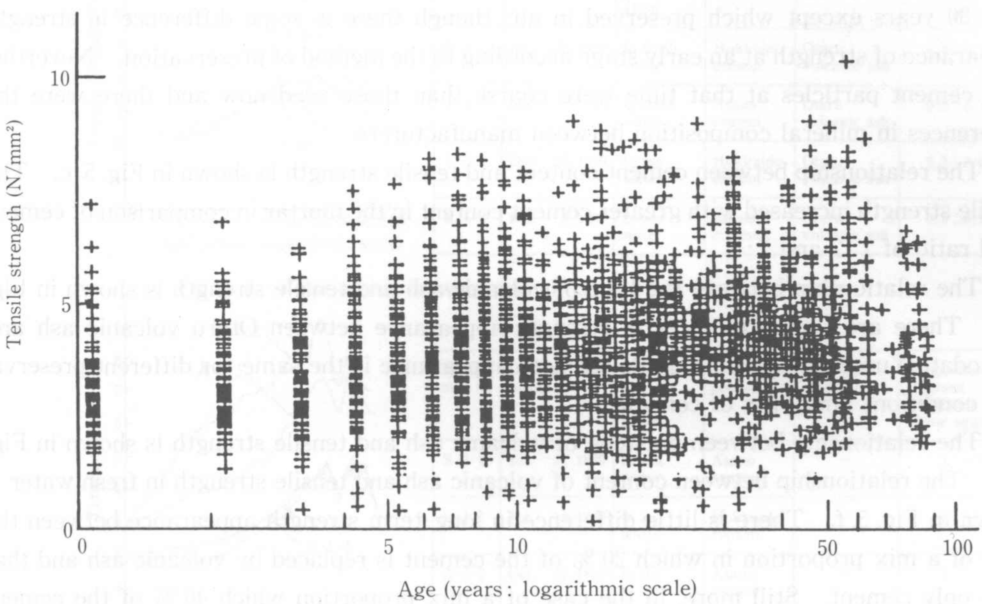


Fig. 3 Relationship between tensile strength and age for all data

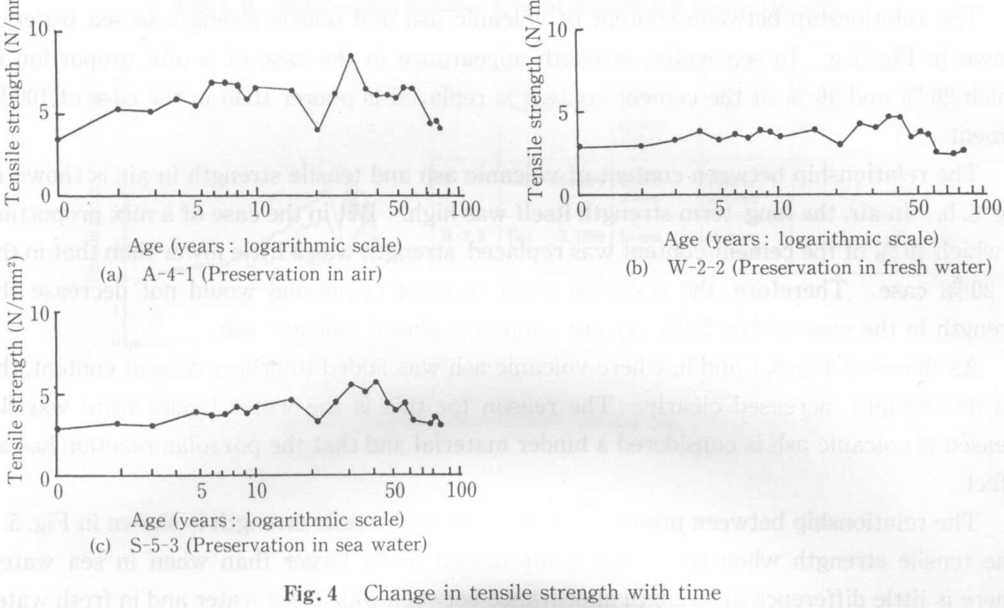


Fig. 4 Change in tensile strength with time

As shown in Fig. 4, the strength of each mix proportion increased with age at an early stage. However the late strength varied widely with some mix proportions. Consequently, the change in strength with time tended to vary. As a first step in the analysis, and to grasp an outline of the change in strength with time, the results are shown as moving averages in Fig. 5. a~i.

The relationship between type of cement and tensile strength is shown in Fig. 5. a and Fig. 5. b. Regarding type of cement, there is no difference in long-term strength at more than 30 years except which preserved in air, though there is some difference in strength appearance of strength at an early stage according to the method of preservation. Nevertheless, cement particles at that time were coarse than those used now and there were the differences in mineral composition between manufacturers.

The relationship between cement content and tensile strength is shown in Fig. 5. c. The tensile strength increased with greater cement content in the mortar in comparison of cement sand ratio of 1 : 2 and 1 : 3.

The relationship between the type of volcanic ash and tensile strength is shown in Fig. 5. d. There are few differences in strength appearance between Otaru volcanic ash and Hakodate Yunosawa clay. Tensile strength appearance is the same for different preservation conditions and types of cement.

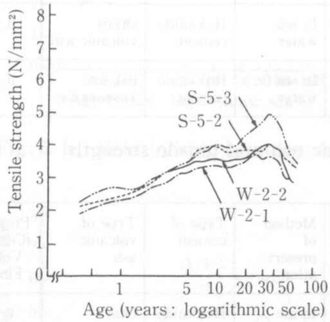
The relationship between existene of volcanic ash and tensile strength is shown in Fig. 5. e. The relationship between content of volcanic ash and tensile strength in fresh water is shown in Fig. 5. f. There is little difference in long-term strength appearance between the case of a mix proportion in which 20 % of the cement is replaced by volcanic ash and that with only cement. Still more, in the case of a mix proportion which 40 % of the cement content is replaced by volcanic ash, strength appearance in fresh water was almost same as that in the case of 100 % cement, though the variation was wide.

The relationship between content of volcanic ash and tensile strength in sea water is shown in Fig. 5. g. In sea water, strength appearance in the case of a mix proportion in which 20 % and 40 % of the cement content is replaced is poorer than in the case of 100 % cement.

The relationship between content of volcanic ash and tensile strength in air is shown in Fig. 5. h. In air, the long-term strength itself was high. But in the case of a mix proportion in which 40 % of the cement content was replaced, strength was a little lower than that in the of 20 % case. Therefore, the pozzolan reaction must occur and would not decrease the strength in the case within 20 % cement content replaced volcanic ash.

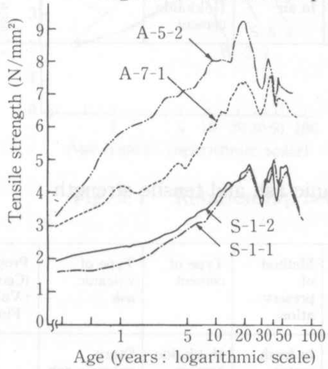
As shown in Fig. 5. f and h, where volcanic ash was added to proper cement content, the tensile strength increased clearly. The reason for this is the water binder ratio was decreased if volcanic ash is considered a binder material and that the pozzolan reaction has an effect.

The relationship between preserving conditions and tensile strength is shown in Fig. 5. i. The tensile strength when preserved in air tended to be larger than when in sea water. There is little difference in strength appearance between was in sea water and in fresh water preservation. In some cases, the strength of preserved in sea water was a little larger than that in fresh water. Therefore, it seems that the effect of dissolving its cement combined component itself in fresh water was more than that of erosion of mortar by certain ingredients in sea water.



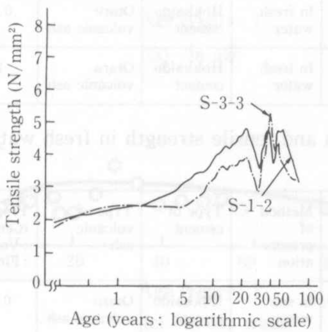
Speci-men No.	Date of manufacture	Method of preserv-ation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
W-2-2	Dec. 13,1909	In fresh water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
W-2-1	Dec. 7,1909	In fresh water	Asano cement	Otaru volcanic ash	0.8 : 0.2 : 3
S-5-3	Dec. 15,1909	In sea water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
S-5-2	Dec. 9,1909	In sea water	Asano cement	Otaru volcanic ash	0.8 : 0.2 : 3

Fig. 5. a Relationship between type of cement and tensile strength



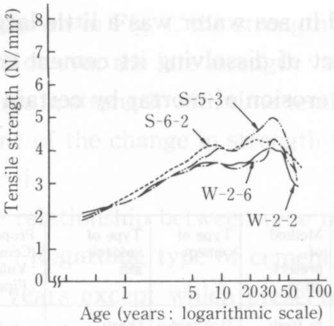
Speci-men No.	Date of manufacture	Method of preserv-ation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
S-1-2	Jul. 22,1899	In sea water	Asano cement	–	1 : - : 2
S-1-1	Jul. 18,1899	In sea water	Hokkaido cement	–	1 : - : 2
A-5-2	Oct. 31,1899	In Air	Asano cement	–	1 : - : 2
A-7-1	Oct. 17,1899	In Air	Hokkaido cement	–	1 : - : 2

Fig. 5. b Relationship between type of cement and tensile strength



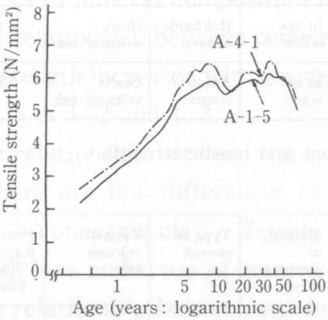
Speci-men No.	Date of manufacture	Method of preserv-ation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
S-1-2	Dec. 15,1899	In sea water	Asano cement	–	1 : - : 2
S-3-3	Dec. 3,1899	In sea water	Asano cement	–	1 : - : 3

Fig. 5. c Relationship between cement content and tensile strength



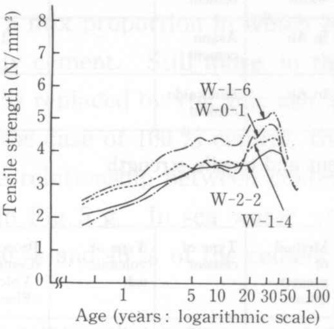
Specimen No.	Date of manufacture	Method of preservation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
W-2-2	Dec. 13,1909	In fresh water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
W-2-6	Feb. 7,1910	In fresh water	Asano cement	Hakodate Yunosawa clay	0.8 : 0.2 : 3
S-5-3	Dec. 15,1909	In sea water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
S-6-2	Mar. 4,1910	In sea water	Hokkaido cement	Hakodate Yunosawa clay	0.8 : 0.2 : 3

Fig. 5. d Relationship between type of volcanic ash and tensile strength



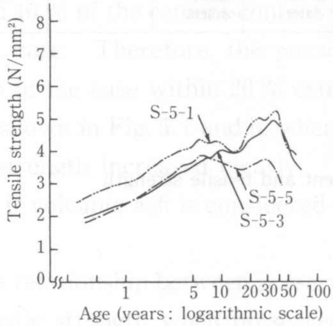
Specimen No.	Date of manufacture	Method of preservation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
A-1-5	Dec. 11,1909	In air	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
A-4-1	Nov. 14,1909	In air	Hokkaido cement	−	1 : - : 3

Fig. 5. e Relationship between content of volcanic ash and tensile strength



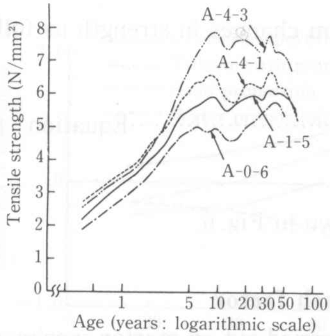
Specimen No.	Date of manufacture	Method of preservation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
W-1-4	Nov. 16,1909	In fresh water	Hokkaido cement	Otaru volcanic ash	1 : - : 3
W-2-2	Dec. 13,1909	In fresh water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
W-0-1	Jan. 9,1909	In fresh water	Hokkaido cement	Otaru volcanic ash	0.6 : 0.4 : 3
W-1-6	Nov. 28,1909	In fresh water	Hokkaido cement	Otaru volcanic ash	1 : 0.5 : 3

Fig. 5. f Relationship between content of volcanic ash and tensile strength in fresh water



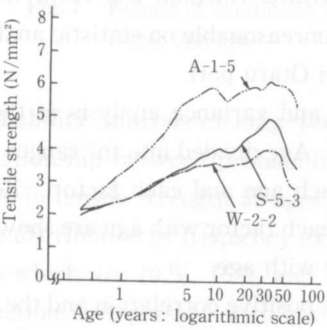
Specimen No.	Date of manufacture	Method of preservation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
S-5-3	Dec. 15,1909	In sea water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
S-5-5	Jan. 13,1910	In sea water	Hokkaido cement	Otaru volcanic ash	0.6 : 0.4 : 3
S-5-1	Dec. 1,1909	In sea water	Hokkaido cement	−	1 : - : 3

Fig. 5. g Relationship between content of volcanic ash and tensile strength in air



Speci-men No.	Date of manufacture	Method of preserv-ation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
A-4-1	Nov. 14, 1909	In air	Hokkaido cement	—	1 : - : 3
A-1-5	Dec. 11, 1909	In air	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
A-0-6	Jan. 7, 1910	In air	Hokkaido cement	Otaru volcanic ash	0.6 : 0.4 : 3
A-4-3	Nov. 26, 1909	In air	Hokkaido cement	Otaru volcanic ash	1 : 0.5 : 3

Fig. 5. h Relationship between content of volcanic ash and tensile strength in sea water



Speci-men No.	Date of manufacture	Method of preserv-ation	Type of cement	Type of volcanic ash	Proportion (Cement : Volcanic ash : Fine aggrigate)
S-5-3	Dec. 15, 1909	In sea water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
W-2-2	Dec. 13, 1910	In fresh water	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3
A-1-5	Dec. 11, 1909	In air	Hokkaido cement	Otaru volcanic ash	0.8 : 0.2 : 3

Fig. 5. i Relationship between preserving condition and tensile strength

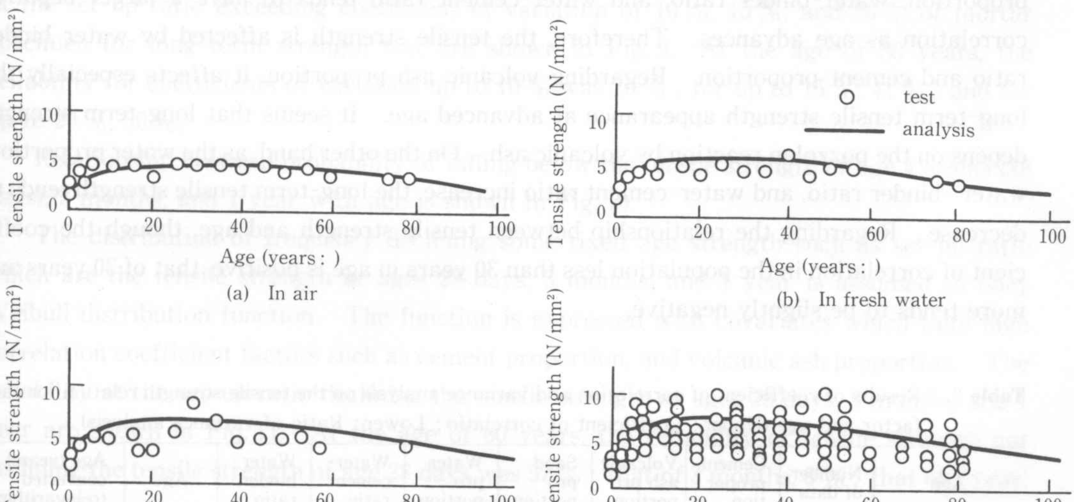


Fig. 6 Results of non-linear analysis (B≠0, volcanic ash ; Otaru volcanic ash)

(2) Analyzing long-term change with exponential function model

In order to analyze long-term change, the authors have developed an exponential function model with weight on long-term aging to express increasing strength with age in a form with a peak. It is well able to express long-term changes in strength as follows.

Tensile strength (N/mm^2)

$=A\times$Age (year)$\times\exp(-C\times$ Age (year)$)+B$ ……………………… Equation (1)

where A, B, and C are constants.

Some typical results of non-linear analysis are shown in Fig. 6.

(3) Correlation analysis and variance analysis of each factor

Correlation analysis and variance analysis were carried out on mortar specimen data in order to grasp quantitatively the effect of each factor on changes in strength with time. The analysis data were pinpointed to the population of Otaru volcanic ash from the whole population, because the number of data points was not unreasonable on statistic analysis and the ash was used in mix proportion for breakwaters in Otaru port.

Some typical results of coefficient of correlation and variance analysis of the tensile strength relation for each factor are shown in Table 2. Age divided into for ranges to make clear the relationship between tensile strength, and each age and each factor. Results of correlation coefficients for the tensile strength against each factor with age are shown in Fig. 7, demonstrating that these coefficients change clearly with age.

With age, the cement proportion ratio tends to have a positive correlation and the volcanic ash proportion tended to have a positive correlation from a negative one. The water proportion, water-binder ratio, and water-cement ratio tends to have a larger negative correlation as age advances. Therefore, the tensile strength is affected by water-binder ratio and cement proportion. Regarding volcanic ash proportion, it affects especially the long-term tensile strength appearance at advanced age. It seems that long-term strength depens on the pozzolan reaction by volcanic ash. On the other hand, as the water proportion, water -binder ratio, and water-cement ratio increase, the long-term tensile strength tends to decrease. Regarding the relationship between tensile strength and age, though the coefficient of correlation in the population less than 30 years in age is positive, that of 30 years and more tends to be slightly negative.

Table 2. Results of coefficient of correlation and variance analysis on the tensile strength relation for each factor and age (Upper: Coefficient of correlatio; Lower: Ratio of variance analysis)

Age	Number of data	Cement proportion	Volcanic ash proportion	Sand proportion	Water proportion	Water-cement ratio	Water-binder ratio	Age	Age (years) converted to logarithm
30>Age	768	0.105 0.0035	−0.167 0.0001	−0.269 0.0069	−0.146 0.0001	−0.076 0.0341	−0.155 0.0001	0.420 0.0001	0.566 0.001
30≦Age<50	85	0.223 0.0403	−0.009 0.9321	−0.197 0.0705	−0.214 0.0488	−0.198 0.0698	−0.242 0.0259	−0.100 0.3608	−0.095 0.3885
50≦Age<70	50	0.379 0.0067	0.242 0.6029	0.000 1.0000	−0.343 0.0147	−0.406 0.0035	−0.365 0.0091	−0.157 0.2805	−0.151 0.2948
70≦Age	26	0.607 0.0010	0.343 0.0860	0.010 0.0721	−0.680 0.0093	−0.648 0.0021	−0.634 0.0061	−0.278 0.1683	−0.277 0.1708

Note: Each proportion by weight

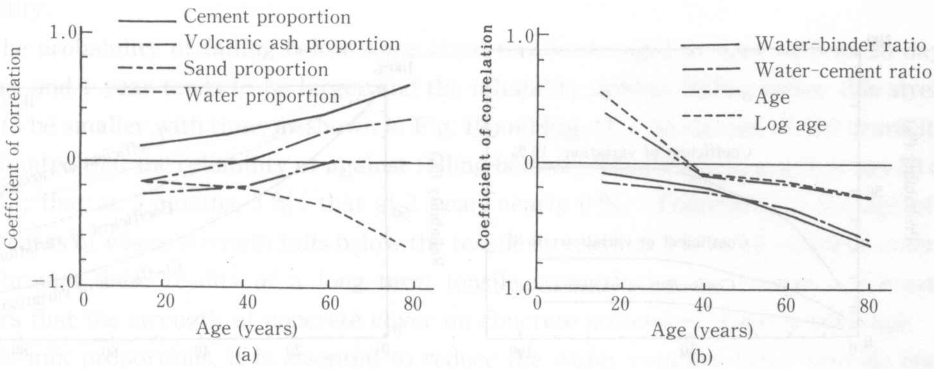


Fig. 7 Results of coefficient of correlation of the tensile strength relation for each factor and age

(4) Reliability analysis of long-term strength and the variation

Relationship between probability to exceeding 10 %, 15 % and 20 % of coefficient of variation in tensile strength at ages is shown in Fig. 8.

The distribution of frequency exceeding some fixed coefficients of variation such as set-up ratio which are 10 %, 15 % and 20 % is assumed to obey Weibull distribution function. The function is expressed with covariates which take high correlation coefficient factors such as cement proportion, volcanic ash proportion, and water-cement ratio. The reliability at the set-up ratio exceeding coefficient of variation of 10 %, 15 %, and 20 % of mortar specimen for long term strength test are shown in Fig. 9. At the age of 80 years, the reliability for coefficients of variation up to 10 % was 20 % ; for up to 15 %, 41 % ; and for up to 20 %, 50 %.

Relationship between probability of falling below the tensile strength of age 4 weeks (28 days), 3 months, and 1 year with age is shown in Fig. 10.

The distribution of frequency declining some fixed age strength such as set-up ratio which are the tensile strength at ages 28 days, 3 months, and 1 year is assumed to obey Weibull distribution function. The function is expressed with covariates which take high correlation coefficient factors such as cement proportion, and volcanic ash proportion. The reliability at the set-up ratio declining the tensile strength at ages 28 days, 3 months, and 1 year are shown in Fig. 11. At the age of 80 years, the reliability of tensile strength not declining the tensile strength of age 28 days was 52 % ; that of 3 months, 5 % ; that of 1 year, nearly 0 %.

3.2 Consideration

Regarding correlation analysis and variance analysis of each factor as shown in Fig. 7, the tensile strength was affected positively by cement proportion and volcanic ash proportion negatively by and water-binder ratio and water-cement ratio. The volcanic ash proportion particularly affected the tensile strength appearance at advanced and long-term age.

Regarding variations in long-term tensile strength, the probability of exceeding some

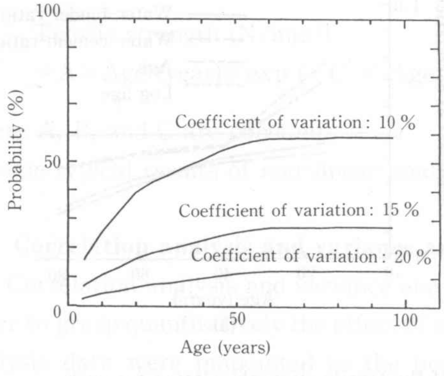


Fig. 8 Relationship between probability of exceeding coefficient of variation of 10 %, 15 %, and 20 % in tensile strength and ages.

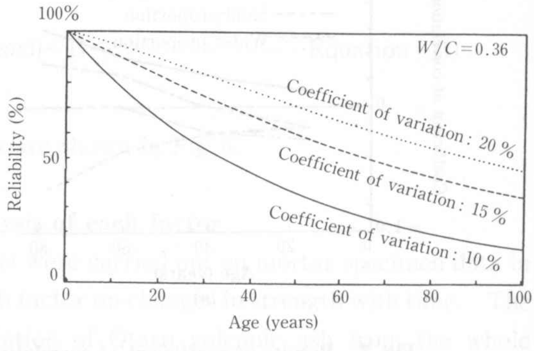


Fig. 9 Relationship between elapsed time t (years) and reliability (R (t)) at set-up ratio of not exceeding coefficient of variation of 10 %, 15 %, and 20 %.

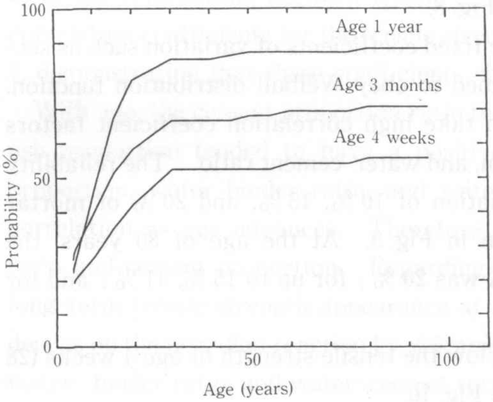


Fig. 10 Relationship between probability of falling below tensile strength of age 1 year, 3 months, and 4 weeks and age

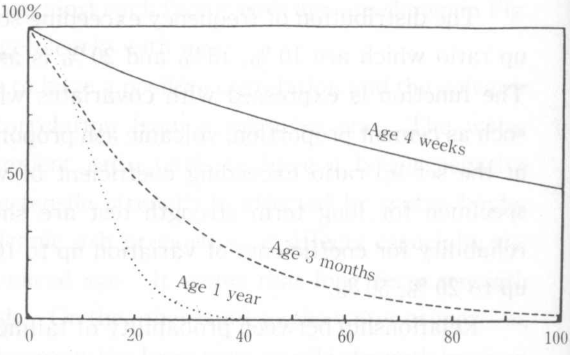


Fig. 11 Relationship between elapsed time t (years) and reliability (R(t)) at set up ratio declining the tensile strength at age 28 days, 3 months, and 1 years.

fixed coefficients of variation, such as set-up ratios of 10 %, 15 %, and 20 %, tends to be larger and the reliability of not exceeding tends these coefficients to be smaller with age as shown in Fig.8 and Fig. 9. At the age of 100 years, it is estimated that the reliability of not exceeding the coefficient of variance of 20 % is 45 % ; of not exceeding 15 % is 35 % ; and of not exceeding 10 % is 15 %. Therefore, the variation in long-term tensile strength tends to be larger with age. For reference, according to the Public Works Research Institute of Japanese Ministry of Construction, the maximum coefficient of variation of concrete is 21 %, and the minimum, 2 % ; the coefficients of variation in 80 % of the studied structures are within 10 %. In comparison with this data, the long-term variations in tensile strength in mortar specimens seem to remain mostly within levels the proper revel giving acceptable reliability.

The probability of falling below some fixed tensile strength at ages such as 28 days, 3 months, and 1 year tends to be larger and the reliability against falling below this strength tends to be smaller with time, as shown in Fig. 10 and Fig. 11. At the age of 100 years, it can be estimated that the reliability of against falling below. The tensile strength at age 28 days is 45 %; that at 3 months, 3 %; that at 1 year, nearly 0 %. Therefore, at the age of 100 years, cases of where strength falls below the tensile strength at 3 months would be common.

Through these results of a long-term tensile strength test on mortar specimens, it appears that the strength of concrete cover on concrete structures changes with age. For durable mix proportions, it is essential to reduce the water-combine ratio, provide enough cement proportion, and add a suitable a mount of volcanic ash proportion to cause a pozzolan reaction in order to maintain good level of strength and the small variation.

4. Conclusion

The following conclusions can be drawn from the analysis and consideration on of this long-term mortar strength.

1) Tensile strength is affected by water-binder ratio, water-cement ratio, and cement proportion.
2) Volcanic ash proportion affects the long-term tensile strength appearance at paticulary at advanced age.
3) Reliability at the set-up ratio not exceeding coefficient of variation of 10%, 15%, and 20 % of mortar specimen for long-term strength test are, at the age 80 years, the reliability within coefficient of variation 10% was 20%; that of 15%, 41%; and that of 20%, 50%.
4) Reliability at the set-up ratio not declining the tensile strength at ages 28 days, 3 months, and 1 year are, at the age 80 years, the reliability of not declining the tensile strength of age 28 days was 52%; that of 3 months, 5%; and that of 1 year, nearly 0%.

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