

Center for By-Products Utilization

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Properties of flowable slurry containing wood ash are presented in this paper. Three series of flowable slurry mixtures were made with three different sources of wood ash. The mixtures were: low-strength slurry (0.3 to 0.7 MPa), medium-strength slurry (0.7 to 3.5 MPa), and high-strength slurry (3.5 to 8 MPa). Tests were performed for flow, density, ambient air and slurry temperature, air content, bleeding, settlement, compressive strength, and permeability. Test results indicate that low-strength slurry mixtures attained a compressive strength of 0.24 to 0.41 MPa at 28-day, whereas it was between 0.97 to 1.38 MPa for medium-strength slurry mixtures., and between 1.59 to

3.24 MPa for high-strength slurry mixtures. 28-day permeability results were between 1.5×10^{-5} to 11×10^{-5} cm/sec for low-strength slurry mixtures, 0.5×10^{-5} and 7.4×10^{-5} cm/sec for medium-strength, and between 0.2×10^{-5} and 1.9×10^{-5} cm/sec for high-strength slurry, respectively. In general, permeability values for all slurry mixtures decreased with an increase in age, whereas compressive strength increased, due to the improved microstructure of slurry mixtures.

Keywords: Bleed-water, cement, CLSM, compressive strength, flowable slurry, permeability, wood ash

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INTRODUCTION

The U.S. pulp and paper mills generate about four million tons of wood ash per year. NCASI has estimated that of the total wood ash, only about 28% is being utilized. The disposal of this large-scale generation of wood ash is a major problem for the industry, mainly pulp mills, saw mills, and energy generating plants that utilize wood and wood residue. The problem concerning the disposal of wood ash in landfills is accentuated by potentially limited landfill space available, strict environmental regulations, and high costs. Co-firing wood residue with coal or other fuels lead to regulatory differentiation between ash from wood residue alone and ash from wood mixed with coal and/or other fuels. Therefore, beneficial utilization options for wood ash is essential for the industry. One of the possible uses of wood ash is in the production of controlled low strength materials (CLSM), also widely known as flowable slurry. CLSM is a high-fluidity cementitious material that flows like a liquid, supports like a solid, and self-levels without compacting. The American Concrete Institute (1) describes CLSM flowable slurry as a cementitious material that is in a flowable state at the time of placement and has specified compressive strength of 8 MPa (1200 psi) or less at the age of 28 days. A number of names including flowable fill, unshrinkable fill, manufactured soil, controlled density fill, flowable mortar, are being used to describe this material. CLSM is used primarily for non-structural applications, such as back-fills, structural-fills, sound insulating and isolation fills, pavement bases, conduit bedding, erosion control, and void filling (1). CLSM is an ideal backfill material. In deciding mixture proportions of CLSM, factors such as flowability, strength, excavatability are evaluated. Permeability is also, for many uses, an important property of CLSM.

Permeability is an indicator of the resistance the material offers against permeation of water, gases, and liquids through it. Permeability of CLSM depends on mixture proportions, properties of constituent materials, water-cementitious material ratio, and age.

RESEARCH SIGNIFICANCE

The principal objective of this investigation was to evaluate the strength and permeability of flowable slurry incorporating wood ash. In this investigation three series of slurry mixtures, low-strength (0.3 to 0.7 MPa), medium-strength (0.7 to 3.5 MPa) and high-strength (3.5 to 8 MPa), were proportioned from three different sources of wood ash. The results of this investigation should be useful in establishing mixture proportions, leaching potential, and production technology for flowable slurry containing wood ash.

LITERATURE REVIEW

Numerous studies by Naik and his associates (2-8), Ramme, et al. (9), Krell (10), Swaffer and Price (11), Larson (12,13), Fuston, et al. (14) have examined and reported on flowable slurry properties, density, strength, settlement, permeability, shrinkage, etc. Lai (15) reported the compressive strength of flowable mortars containing high-volume coal ash applicable for back-fill or base course construction. It was mentioned that the 28-day compressive strength of about 1 MPa can be achieved for the specimens with 6% cement, by weight, at excellent flowability. Naik, et al. (8) developed excavatable CLSM mixtures having compressive strength between 0.3 to 0.7 MPa (50 to 100 psi) at

age of 28 days. Naik and Singh (4) have reported on permeability of slurry materials (0.3 to 0.7 MPa) containing used foundry sand and fly ash as 3×10^{-6} to 74×10^{-6} cm/s. Tikalsky, et al. also (16) evaluated the potential of used foundry sand as a constituent of controlled low-strength material (CLSM), and concluded that used foundry sands provide high-quality material for CLSM. Tikalsky, et al. (17) evaluated clay-bonded and chemically bonded CLSM sand and compared them in the plastic and hardened states to CLSM mixtures containing uniformly graded crushed limestone sand. Test results showed that used foundry sand can be successfully used in CLSM and it provided similar or better properties to that of CLSM containing crushed limestone. Horiguchi, et al. (18) evaluated the potential use of off-specification fly ash plus non-standard bottom ash in CLSM. Total of 20 mixtures were tested for flowability, bleeding, and short-term and long-term compressive strengths. Test results indicated that there is an optimum combination of fly ash to bottom ash ratio for the desirable physical properties of CLSM. CLSM with off-specification fly ash and non-standard bottom ash showed excellent performance indicating ecological and economical applicability to CLSM. Horiguchi, et al. (19) also investigated physical and durability characteristics of CLSM made with used foundry sand and bottom ash as fine aggregates. Based on the test results, they concluded that the frost heaving rate of CLSM with used foundry sand and bottom ash was less than 3%, which is a relatively smaller value compared to soil-like materials. Naik, et al. (20) developed two types of CLSM or flowable slurry utilizing post-consumer glass aggregate and fly ash. Type A CLSM consisted of glass, fly ash, cement, and water; and Type B CLSM consisted of glass, sand, cement, and water. They concluded that the flowable slurry developed, satisfied the ACI Committee 229 requirements (1).

Gassman, et al. (21) examined the effects of prolonged mixing and re-tempering on the fluid- and hardened-state properties of CLSM. The test results showed that extending the mixing time beyond 30 minutes decreased unconfined compressive strength and delayed the time of setting. Re-tempering did not affect the 28-day strength; however, it did affect the 90-day strength depending upon the mixing time. There are insufficient data available for the permeability of slurry materials, especially CLSM containing wood ash. Furthermore, there is a general lack of any information available for use of wood ash in flowable slurry.

EXPERIMENTAL PROGRAM

Materials

Type-I portland cement from Lafarge Corporation, conforming to ASTM C 150, was used in this investigation. Wood ash from three different sources were used, W1, W2, and W3. W1 was obtained from Niagara, Wisconsin, W2 from Biron, Wisconsin, and W3 from Rothschild, Wisconsin. Physical properties and chemical composition of all the three sources of wood ash are presented in Tables 1 and 2, respectively. The fine aggregate used was natural sand with $\frac{1}{4}$ in. maximum size, having specific gravity 2.64 and fineness modulus 2.7. Their physical properties were determined per ASTM C 33. It was obtained from a local ready-mixed concrete company and it satisfied all requirements of ASTM C33.

Mixture Proportions

Three series of slurry mixture were proportioned for the three different sources of wood ash, low-strength slurry mixtures designated as 1-L through 3-L, medium-strength slurry mixtures designated as 1-M through 3-M, and high-strength slurry mixtures designated as 1-H through 3-H. Mixture proportions for low-strength, medium-strength, and high-strength slurry mixtures are presented in Table 3.

Manufacturing Technique

The flowable slurry was mixed in a 0.25-m³ capacity electrically driven rotating drum mixer. The slurry ingredients were weighed and loaded in the mixer in the following manner. Initially, the required amount of cement and half the amount of wood ash and/or sand was loaded in the mixer and mixed for three minutes. Three quarters of the specified water was added to the mixer and mixed for an additional three minutes. The remaining wood ash and/or sand and water were added to the mixer and mixed for additional five minutes. The remaining ingredients were added to the mixer and mixed for an additional minimum three minutes. Additional water was added in smaller quantities to ensure reaching the required flow/consistency. The flow/spread, air content, temperature, density, etc. were determined for each mixture before casting test specimens. Results are presented in Table 3.

Preparation and Testing of Specimens

The strength test specimens were cast in 150 x 300 mm cylindrical plastic molds for measurement of plastic properties as well as compressive strength of the flowable

slurry materials. The permeability specimens were cast in 100 x 125 mm cylindrical plastic molds. All specimens were prepared in accordance with ASTM C 192.

Fresh slurry was tested for flow/spread in accordance with ASTM D 6103, “Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)”. The temperature of the slurry and ambient air temperature was measured and recorded. The unit weight and air content was determined in accordance with ASTM D 6023, “Standard Test Method for Unit Weight, Cement Content, and Air Content of Controlled low Strength Material (CLSM)”. Compressive strength was determined at the ages of 7, 14, 28, and 91 days in accordance with ASTM D 4832, “Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders”. The permeability of the slurry was tested at 28 and 91 days in accordance with ASTM D 5084, “Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials using a flexible Wall Permeameter”.

TEST RESULTS AND ANALYSIS

Plastic Properties

The properties of flowable slurry materials examined were flow/spread, temperature, unit weight, air content, bleed water, and settlement. Results of flow/spread, temperature, air content and unit weight of slurry Series L, M, and H are given in Table 3. The unit weight of the slurry material was found to be in the range of 1194–2034 kg/m³. Bleeding is the upward movement and accumulation of water in a mixture. It was measured as the depth of water above the CLSM mixture level in a (150 x 300 mm) plastic cylindrical mold. For Series L slurry mixtures, the initial bleed water

accumulated was between 1.5 to 9.5 mm within one hour. For Mixtures 1-L and 2-L evaporation of bleed water took place between 1 to 8 hours, whereas Mixture 3-L recorded up to 1.5 mm of bleed water until 3 days. For series M slurry mixtures, the initial bleed water accumulated was 4.5 to 12 mm within one hour. For Mixtures 1-M, 2-M, and 3-M evaporation of bleed water took place between 4 to 48 hours. For Series-H slurry, the initial bleed water accumulated was between 4.5 to 9.5 mm in one hour. For Mixtures 1-H, 2-H, and 3-H evaporation of bleed water took place within 8 hours,

Compressive Strength

The compressive strength data for the three slurry mixtures tested are presented in Figs 1-3. The low-strength slurry mixtures were proportioned to have a compressive strength between 0.3 to 0.7 MPa at the age of 28 days. Test results of compressive strengths at 7, 14, 28 and 91 days are shown in Fig. 1. At the age of 7-day, Mixtures 1-L, 2-L, and 3-L achieved compressive strength of 0.17 MPa, 0.14 MPa, and 0.17 MPa, respectively. The values obtained were 0.38 MPa, 0.24 MPa, and 0.41 MPa for Mixtures 1-L, 2-L, and 3-L at 28-day. Compressive strength of Series L mixtures continued to increase up to 91-day testing. Slurry Mixture 2-L had higher air-content of 5.5%, which could have led to reduced strength.

The medium-strength slurry mixtures were proportioned to have a compressive strength between 0.7 to 3.5 MPa at the age of 28 days. Compressive strength results of medium-strength slurry mixtures at 7, 14, 28 and 91 days are shown in Fig. 2. Mixtures 1-M, 2-M, and 3-M achieved compressive strength of 0.34 MPa, 0.55 MPa, and 0.66 MPa, respectively, at the age of 7-day testing. The compressive strength values at 28-

day were 1.38 MPa, 0.97 MPa, and 1.28 MPa for Mixtures 1-M, 2-M, and 3-M. The mixture proportions for these series had higher cement content than Series L mixtures. All mixtures satisfied the 28-day age compressive strength requirement.

The high-strength slurry mixtures were proportioned to have a compressive strength between 3.5 to 8 MPa at 28 days of testing. Compressive strength results of high-strength slurry mixtures are shown in Fig. 3. 7-day testing showed high-strength slurry Mixtures 1-H, 2-H, and 3-H achieving strength values of 1.38 MPa, 1.06 MPa, and 2.28 MPa, respectively. The compressive strength values obtained at 28-day were 3.24 MPa, 1.59 MPa, and 3.10 MPa for Mixtures 1-H, 2-H, and 3-H. At 91-day, Mixtures 1-H, 2-H, and 3-H gained strength of 6.66 MPa, 8.62 MPa, and 4 MPa, respectively. Mixture 2-H resulted in a lower compressive strength at 28-day age probably due to higher air content recorded, Table 3.

Permeability

Permeability test results at 28 days and 91 days are shown in Figs. 4, 5, and 6 for low-strength, medium-strength, and high-strength mixtures, respectively. The permeability test results for Series L slurry mixtures were between 1.5×10^{-5} cm/s and 11.0×10^{-5} cm/s at the age of 28 days. The permeability values of all the slurry mixtures further decreased with an increase in age. This is due the increase in compressive strength because of continuing pozzolanic and cementitious reactions in the matrix, resulting in denser matrix. Mixture 2-L permeability essentially remained the same at 28 day and 91day test ages.

The permeability results for Series M mixtures are shown in Fig. 5. The values were between 0.5×10^{-5} cm/s and 7.4×10^{-5} cm/s at 28-day. Permeability of Mixture 2-M could not be measured properly. Therefore, results are not presented here. The permeability values of all slurry mixtures decreased with an increase in age due to the increase in strength from continuing pozzolanic reactions due to wood ash.

The permeability test results for Series H mixtures were between 0.2×10^{-5} cm/s and 1.9×10^{-5} cm/s at the 28-day age. Mixture 2 H recorded a low permeability of 0.2×10^{-5} cm/s, while Mixture 3 H recorded a high permeability of 1.8×10^{-5} cm/s. Low permeability value of Mixture 2 H could be attributed to higher cement content of 205 kg/m³, which could have provided early hydration than other mixtures, leading to denser matrix. Mixture 3-H had the highest amount of fine aggregate of 947 kg/m³. This increase in permeability could be attributed to the increase in voids produced by the increase in sand content for this slurry mixture

CONCLUSIONS

Following are the general conclusions of this investigation based on the data reported.

1. Three sources of wood ash, W1, W2, and W3 used in this investigation, did not conform to the ASTM C 618 requirement for coal fly ash. However, it is shown that they can be used as a main component in flowable slurry.
2. Compressive strength values at 28-day for low-strength slurry mixtures were between 0.24 and 0.41 MPa, whereas it was between 0.97 to 1.38 MPa for

medium-strength slurry mixtures, and between 1.59 to 3.24 MPa for high-strength slurry mixtures.

3. The wood ash from all the three sources produced a significant increase in compressive strength at later ages due to continuing pozzolanic reaction.
4. Permeability results at 28-day were, between 1.5×10^{-5} to 11×10^{-5} cm/sec for low-strength slurry mixtures, 0.5×10^{-5} and 7.4×10^{-5} cm/sec for medium-strength, and between 0.2×10^{-5} and 1.9×10^{-5} cm/sec for high-strength slurry.
5. The permeability of the slurry mixtures decreased as the test age increased from 28-day to 91-day. The permeability values increased due to the significant increase in strength due to continuing pozzolanic reaction.

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Table 1. Physical Properties of Wood Ash Used

Test	Source			ASTM C 618 Requirements for coal fly ash		
	W1	W2	W3	Class C	Class F	Class N*
Retained on No. 325 sieve (%)	23	60	90	34 Max.	34 Max.	34 Max.
Strength Activity Index with Cement, % of Control						
3 days	88.4	38.4	102.0**			
7 days	84.2	39.4	83.3**	75 Min.	75 Min.	75 Min.
28 days	88.3	33.6	78.7**	75 Min.	75 Min.	75 Min.
Water Requirement, % of Control	115	155	115	105 Max.	105 Max.	115 Max.
Autoclave Expansion, %	0.2	0.5	-0.63**	± 0.8	± 0.8	± 0.8
Unit Weight, kg/m ³	550	412	1376	--	--	--
Specific Gravity	2.26	2.41	2.60	--	--	--
Variation from Mean, %						
Fineness	0.5	0.7	0.6**	5 Max.	5 Max.	5 Max.
Specific Gravity	0.1	0.0	1.9	5 Max.	5 Max.	5 Max.

* Volcanic ash

** Material passing No. 100 (150 µm) sieve was used for this test.

Table 2. Chemical Composition of Wood Ash Used

Analysis Parameter	Source			ASTM Requirement C 618 for Coal Fly Ash		
	W1	W2	W3	Class C	Class F	Class N*
Silicon Dioxide, SiO ₂ (%)	32.4	13.0	50.7	--	--	--
Aluminum Oxide, Al ₂ O ₃ (%)	17.1	7.8	8.2	--	--	--
Iron Oxide, Fe ₂ O ₃ (%)	9.8	2.6	2.1	--	--	--
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	59.3	23.4	61.0	50 Min.	70 Min.	70 Min.
Calcium Oxide, CaO (%)	3.5	13.7	19.6	--	--	--
Magnesium Oxide, MgO (%)	0.7	2.6	6.5	--	--	--
Titanium Oxide, TiO ₂ (%)	0.7	0.5	1.2	--	--	--
Potassium Oxide, K ₂ O (%)	1.1	0.4	2.8	--	--	--
Sodium Oxide, Na ₂ O (%)	0.9	0.6	2.1	--	--	--
Sulfite, SO ₃ (%)	2.2	0.9	0.1	5 Max.	5 Max.	4 Max.
LOI (1000°C) (%)	31.6	58.1	6.7	6 Max.	6 Max.**	10 Max.
Moisture (%)	2.4	0.5	0.2	3 Max.	3 Max.	3 Max.
Available Alkali, Equivalent Na ₂ O (%)	0.9	0.4	0.8	1.5 Max.	1.5 Max.	1.5 Max.

* Volcanic ash

** The use of Class F pozzolan containing up to 12% loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Table 3. Mixture Proportions

	Low-Strength CLSM			Medium-Strength CLSM			High-Strength CLSM		
	1-L	2-L	3-L	1-M	2-M	3-M	1-H	2-H	3-H
Mixture Number									
Wood Ash Source	W1	W2	W3	W1	W2	W3	W1	W2	W3
Wood Ash (%)	90	85	90	75	65	90	70	50	75
Cement (kg/m ³)	77	89	53	187	229	101	169	205	196
Wood Ash (kg/m ³)	642	469	1188	612	401	1135	428	205	538
Water (kg/m ³)	627	636	481	603	597	511	419	431	359
[W/(C+WA)]	0.87	1.13	0.39	0.87	1.13	0.39	0.7	1.05	0.48
SSD Fine Aggregate (kg/m ³)	0	0	0	0	0	0	775	829	947
Flow/spread (mm)	241	254	254	273	260	254	273	260	273
Air content (%)	2.4	5.0	3.5	1.5	5.7	4.4	1.4	6.3	1.6
Air temperature (°C)	22.2	22.2	22.2	25.6	25.6	25.6	25.6	26.1	25.6
Slurry temperature (°C)	23.3	23.3	23.9	22.2	27.8	25.6	23.3	27.8	28.9
Slurry Density (kg/m ³)	1342.4	1193.6	1721.6	1396.8	1224	1747.2	1785.6	1662.4	2033.6

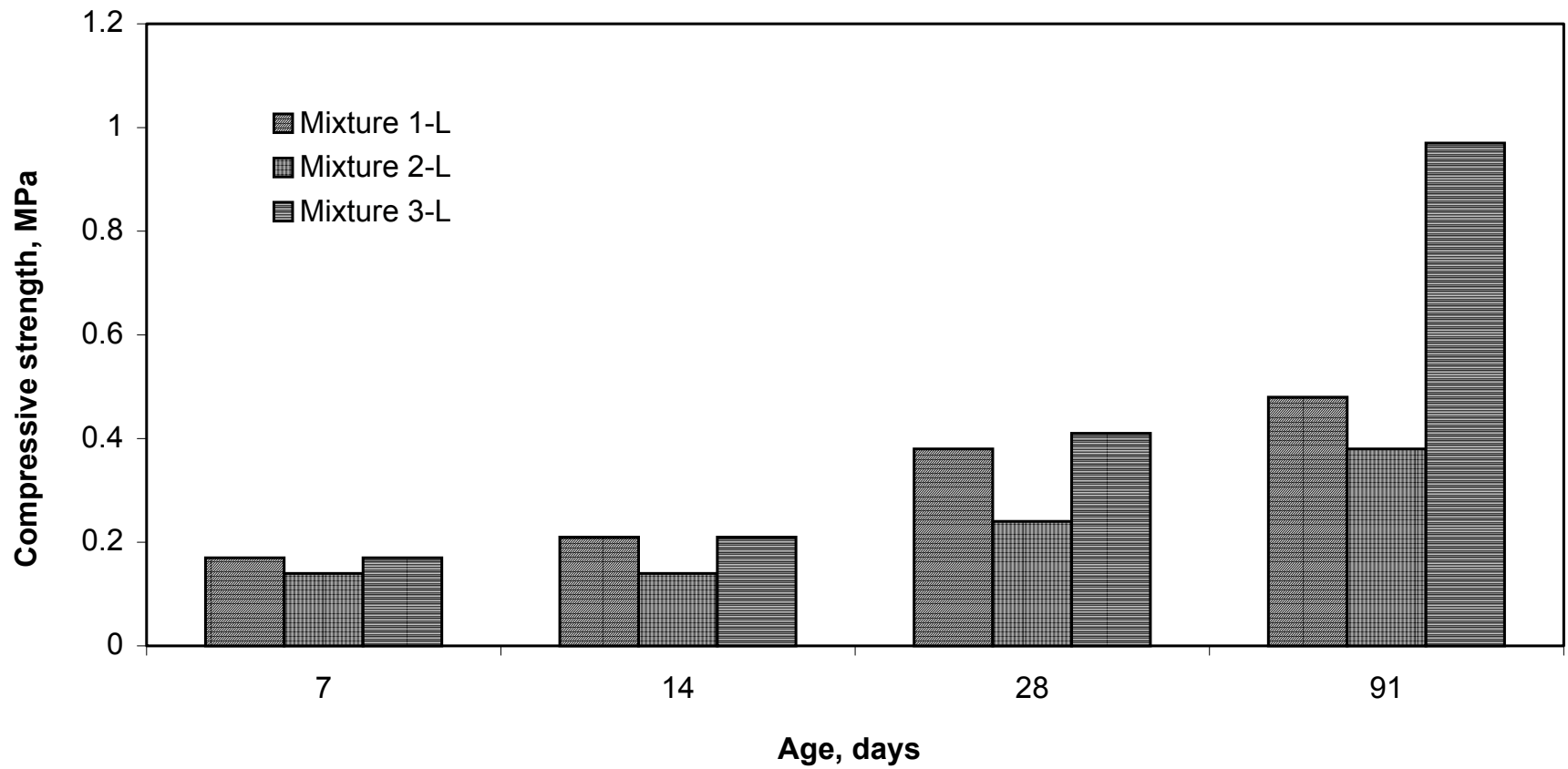


Fig. 1 Compressive strength of low-strength CLSM mixtures versus age

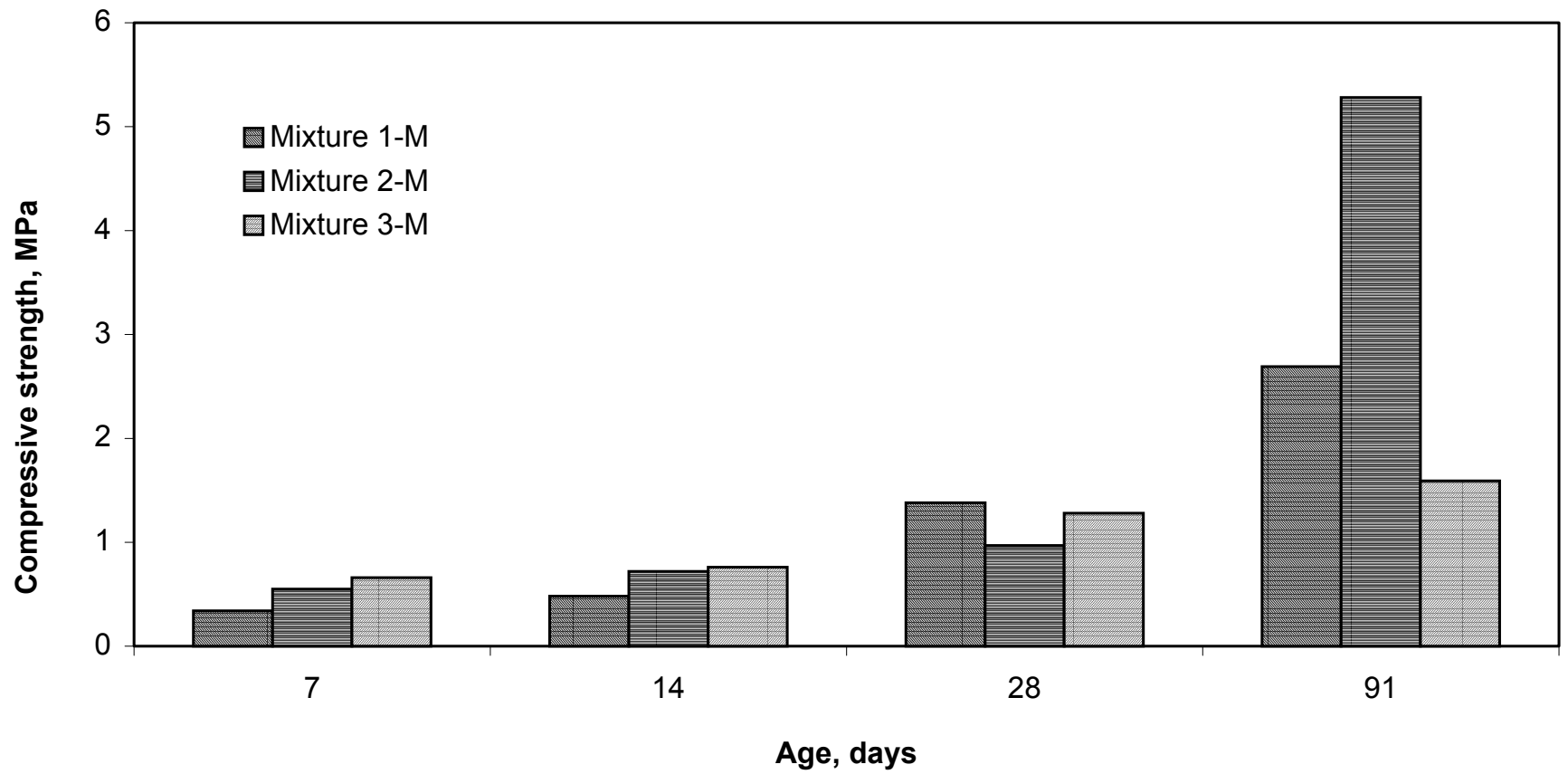


Fig. 2 Compressive strength of medium-strength CLSM mixtures versus age

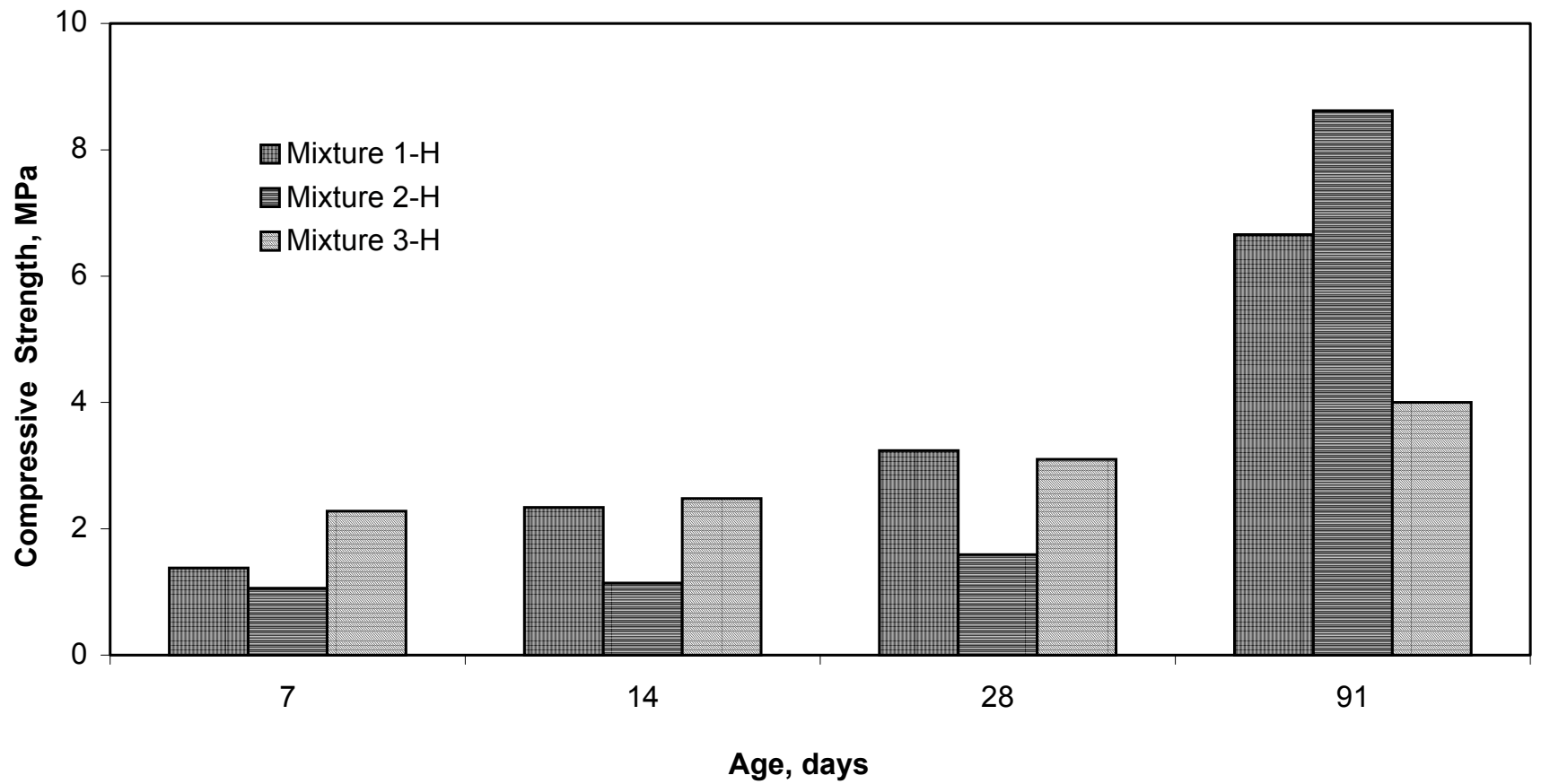


Fig. 3 Compressive strength of high-strength CLSM Mixtures versus age

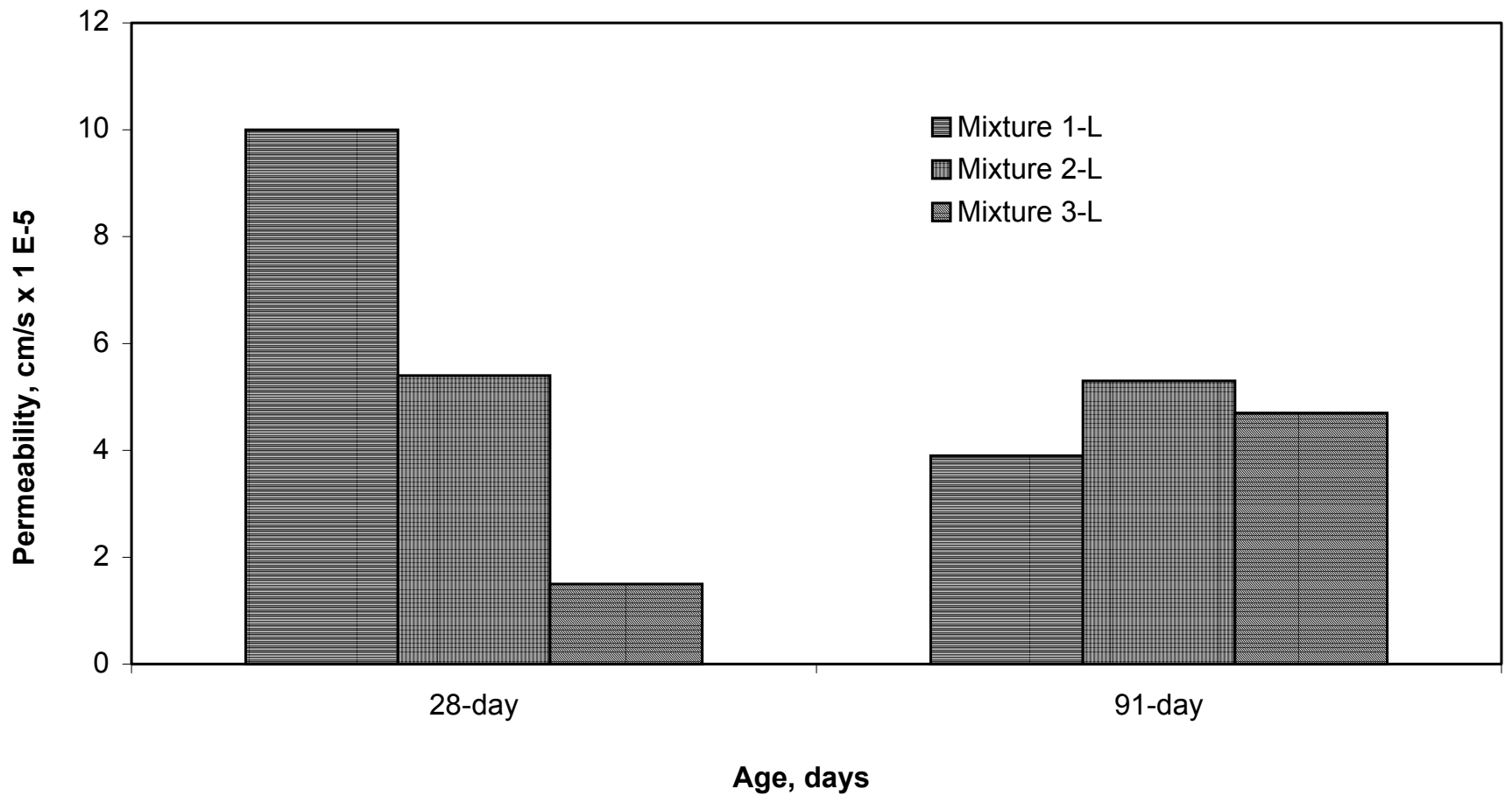


Fig. 4 Permeability of low-strength CLSM mixtures versus age

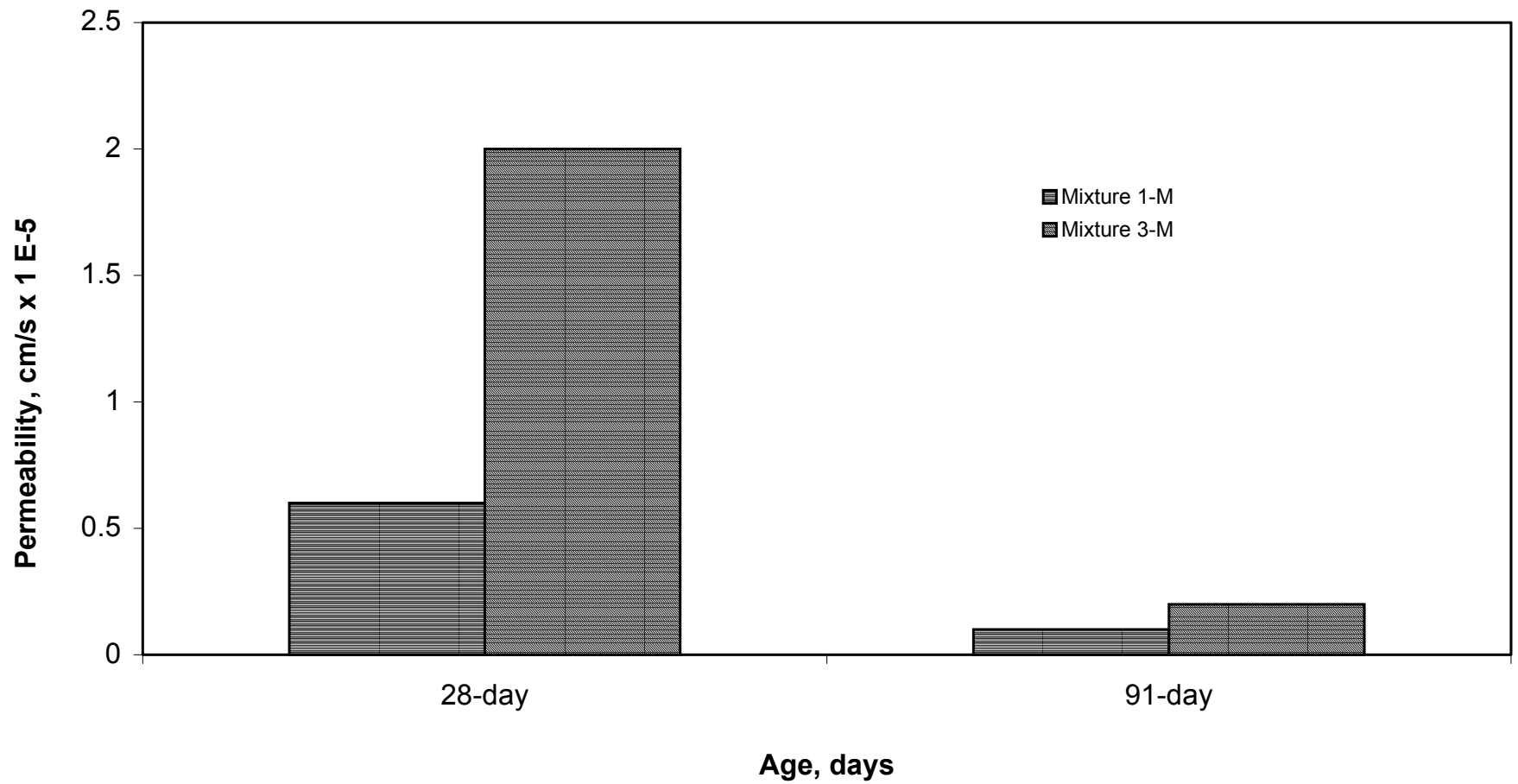


Fig. 5 Permeability of medium-strength CLSM mixtures versus age

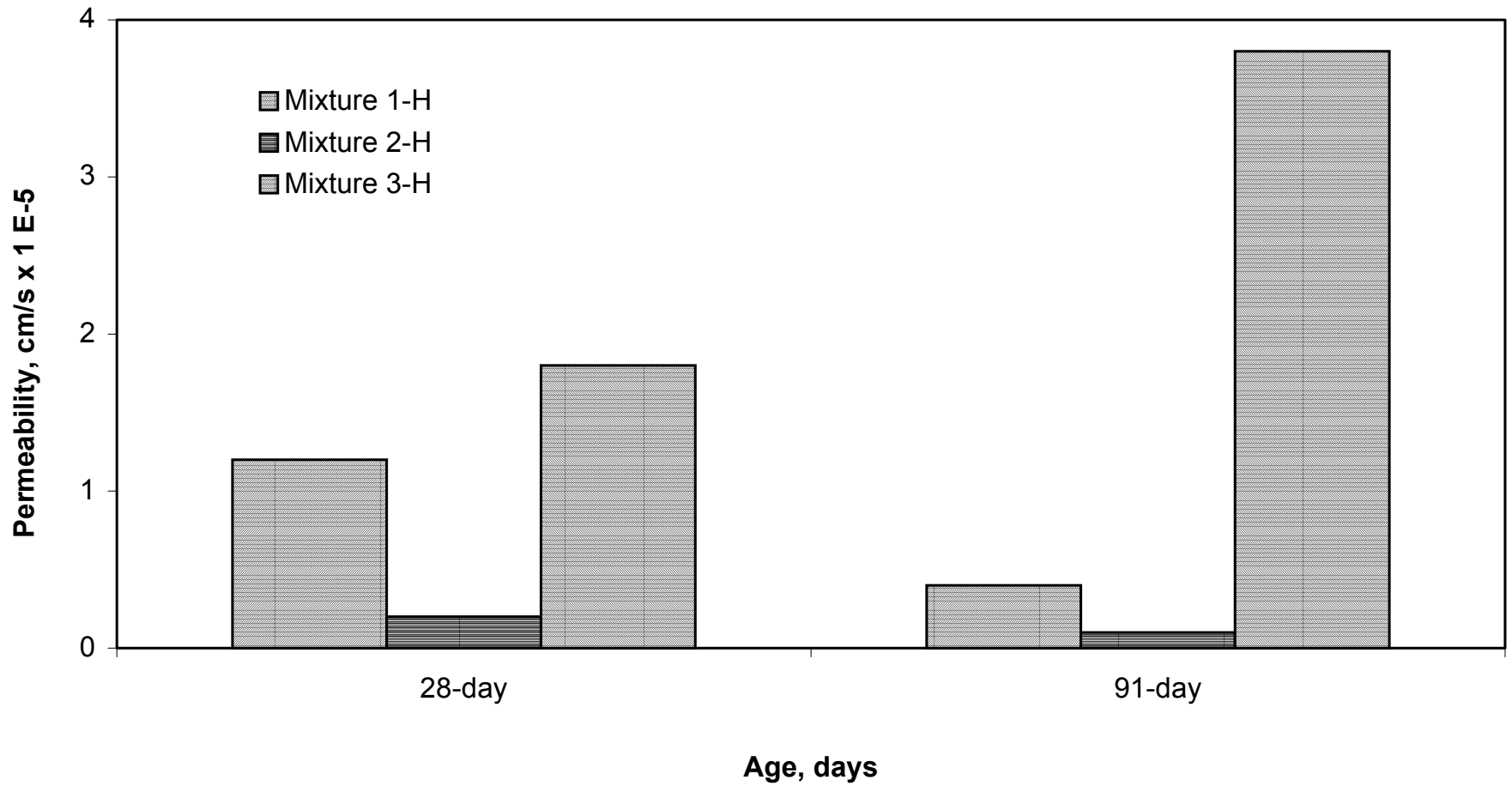


Fig. 6 Permeability of high-strength CLSM mixtures versus age