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REVIEW ARTICLE

Recent Progress in Concrete-Polymer Composites

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This review deals with the recent progress of developments in concrete-polymer composites, which are classified into three types: polymer-modified (or cement) mortar (PMM) and concrete (PMC), polymer mortar (PM) and concrete (PC), and polymer-impregnated mortar (PIM) and concrete (PIC). A great interest in the concrete-polymer composites is currently focused on high-grade redispersible polymer powders, repair and durability-improving materials for reinforced concrete structures, mass production systems, automated cast-in-place application systems, artificial marble products, machine tool structures, and field polymer impregnation systems. Environment-conscious developments are also conducted in the concrete-polymer composites. ADVANCED CEMENT BASED MATERIALS 1997, 5, 31–40. © *1997* ELSEVIER SCIENCE LTD.
KEY WORDS: Concrete-polymer composites, Developments, Environmental issues, Polymer-impregnated mortar (PIM) and concrete (PIC), Polymer-modified (or cement) mortar (PMM) and concrete (PMC), Polymer mortar (PM) and concrete (PC).

In recent years, technical innovations in the construction industry have progressed considerably, and the research and development of high-performance and multifunctional construction materials have been actively pursued to cope with the innovations. In particular, this trend is marked in the new frontiers of the construction industry, i.e., super-high-rise building, very deep underground space, ocean, and lunar base developments in advanced countries. Current development of construction materials should be ecologically safe and energy-saving from the viewpoint of global environment protection, apart from conventional development. There are concrete-polymer composites in construction materials toward which a great interest is oriented. A worldwide interest in concrete-polymer composites has become stronger, and since 1990 eight international congresses, symposiums, and workshops have been held as listed in Table 1.

Concrete-polymer composites are the materials which are made by replacing a part or all of the cement hydrate binder of conventional mortar or concrete with polymers, and by strengthening the cement hydrate binder with polymers. The concrete-polymer composites are generally classified into the following three types by the principles of their process technology:

1. Polymer-modified (or cement) mortar (PMM or PCM) and concrete (PMC or PCC)
2. Polymer mortar (PM) and concrete (PC)
3. Polymer-impregnated mortar (PIM) and concrete (PIC)

Figure 1 shows the system and classification of the concrete-polymer composites [1].

The present review deals with the recent progress in the developments of concrete-polymer composites activities and standardization work regarding them in the industry.

Recent Progress in Polymer-Modified Mortar and Concrete

For the past 70 years or more, the active research and development of polymer-modified mortar and concrete have been performed in various countries. As a result, polymer-modified mortar and concrete became the dominant materials in the construction industry in the 1980s, and are currently used as popular construction materials. In Japan, polymer-modified mortar is most widely used as a construction material for finish and repair work, but polymer-modified concrete is seldom used because of its poor cost-performance balance. However, the polymer-modified concrete is widely used for bridge deck overlays and patching work in the United States. In particular, it is estimated that each year over 1.2 million m^2 of bridge decks are overlaid with polymer-modified concrete [2]. In recent years, about 60,300 m^3 of polymer-modified concrete has been placed each year on both new and existing deteriorated concrete structures in the United States [3].

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TABLE 1. Major international congresses, symposiums and workshops on polymers in concrete

Year	Venue	Congress, Symposium or Workshop Name
1990	Shanghai, China	Sixth International Congress on Polymers in Concrete
1991	Bochum, Germany	International Symposium on Concrete-Polymer Composites
1991	San Francisco, U.S.A.	ACI-ICPIC North American Workshop on Polymers in Concrete
1992	Johannesburg, South Africa	Second South African Conference on Polymers in Concrete
1992	Moscow, Russia	Seventh International Congress on Polymers in Concrete
1993	Salvador, Brazil	ICPIC/IBRACON Workshop on Polymers in Concrete
1994	Chuncheon, Korea	First East Asia Symposium on Polymers in Concrete
1995	Oostende, Belgium	Eighth International Congress on Polymers in Concrete

To produce polymer-modified mortar and concrete, mostly polymers in dispersion (latex or emulsion) form are added to ordinary cement mortar and concrete during mixing. Polymer-modified mortar and concrete have considerable attraction because their process technology is very similar to that of ordinary cement mortar and concrete. Figure 2 represents the classification of polymeric admixtures or modifiers for polymer-modified mortar and concrete. The polymer dispersions widely used are styrene-butadiene rubber (SBR) latex, ethylene-vinyl acetate (EVA), and polyacrylic ester (PAE) emulsion in Japan and Europe, and the styrene-butadiene rubber latex, polyacrylic ester emulsion, and epoxy (EP) resin in the United States. Annual consumption of the polymer dispersions in Japan has exceeded 100,000 tons in recent years. In Japan and Europe, the epoxy resin is rarely used as a polymeric admixture because it is more expensive than latex or emulsion polymers. In Europe, Japan, and the United States, redispersible polymer powders are produced by spray-drying polymer dispersions such as ethylene-vinyl acetate and vinyl acetate-vinyl carboxylate emulsions, and often employed for the same purpose as polymer dispersions. Various water-soluble polymers such as methyl cellulose (MC), hydroxy ethyl cellulose (HEC), polyvinyl alcohol (PVAL), polyacrylamide, and acrylate monomer are used as polymeric admixtures for plastering work or underwater concreting work, and macrodefect-free (MDF) cements.

Tables 2 and 3 list recent developments in polymer-modified mortar and concrete. Some comments on the recent developments in the polymer-modified mortar and concrete are given below.

In recent years, the quality of redispersible polymer powders has improved markedly. In particular, film

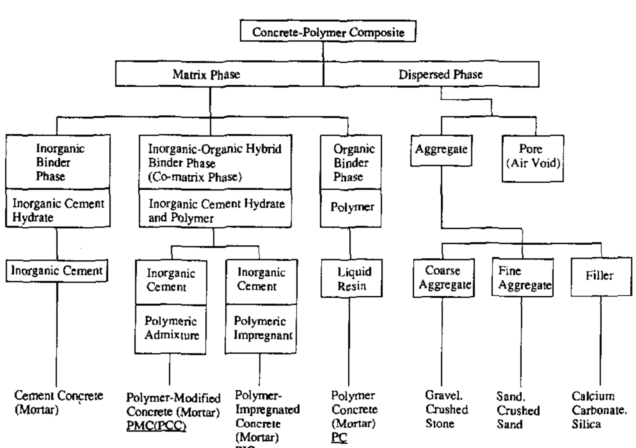

FIGURE 1. System and classification of concrete-polymer composites.

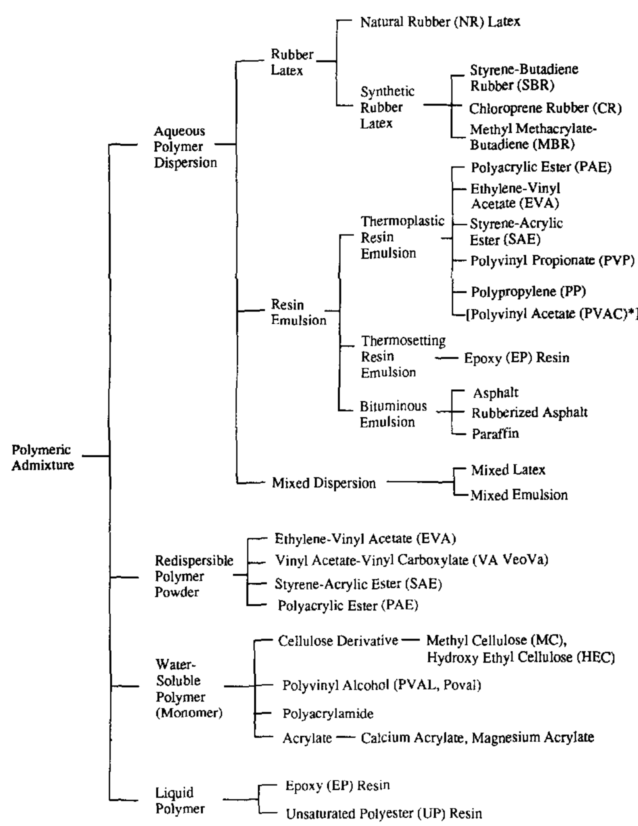

FIGURE 2. Classification of polymeric admixtures (or modifiers) for polymer-modified mortar and concrete. Note, *At present, PVAC is not used because of its poor water resistance.

TABLE 2. Recent developments in polymer-modified mortar and concrete (Part 1)

Topic	Outline
1. High-grade redispersible polymer powders	Marked quality improvement of redispersible polymer powders (EVA, VAVeoVa, SAE and PAE) for PMM, and the development of prepackaged-type products such as decorative wall coatings, tile adhesives and filling compounds for surface preparation, using the redispersible polymer powders [4,5]
2. Combined use of polymer dispersions and chemical admixtures	(1) Development of polymeric admixtures consisting of polymer dispersions (latexes or emulsions) and chemical admixtures such as alkyl alkoxy silanes [6], calcium nitrite as a corrosion inhibitor [7] and amino alcohol derivative [6] for highly durable concrete (2) Combined use of polymer dispersions (latexes or emulsions) and superplasticizers [8,9] (3) Combined use of polymer dispersions (latexes or emulsions) and an EP resin [10]
3. Combined use of polymer dispersions and mineral admixtures	Combined use of polymer dispersions and fly ash [11] or silica fume [12]
4. New epoxy modification systems	Development of PMM and PMC using an EP resin without any hardener at polymer-cement ratios of 5 to 20% [13,14]
5. Unique PMM	(1) UP-modified systems [15,16] (2) Vegetable oil-modified mortars [17] (3) Development of precast products manufactured by using superabsorbent polymers such as polyacrylates and applying compression or extrusion molding process [18]
6. Polymeric modification for fiber reinforced mortars and concretes, and ferrocements	(1) Polymer modification of fiber-reinforced cement mortars and concretes using steel, glass, polymer and carbon fibers [19–22] (2) Polymer modification of ferrocements [23,24]
7. MDF cements	(1) Development of new MDF cements using an anhydrous phenol resin precursor, which have flexural strengths of 120 to 220 MPa and very high water resistance [25,26] (2) Improvement in water resistance of MDF cements [27,28] (3) Fiber reinforcement of MDF cements [29]

formation characteristics and properties of polymer-modified mortars and concretes using redispersible polymer powders have become similar to those of polymer-modified mortars and concretes using polymer dispersions. It is suggested from this fact that polymer dispersions will be replaced by redispersible polymer powders in the production of polymer-modified mortars and concretes in the near future.

When the combined use of polymer dispersions and chemical admixtures advances further, new multifunctional chemical admixtures for cement concrete will successfully be developed.

Polymer-modified mortars and concretes using an epoxy resin without any hardener at polymer-cement ratios of 5 to 20% are the epoxy-hydraulic cement systems of new concept, and will develop the new applications of epoxy-modified mortars and concretes.

For the purpose of improving the workability, drying shrinkage, and durability of fiber-reinforced cements and concretes, or increasing the flexural strength, toughness, and impact resistance of polymer-modified mortars and concretes, fiber-reinforced polymer-modified cements and concretes are produced using steel, glass, polymer, and carbon fibers. In particular, polymer modification of glass fiber-reinforced cements is very effective in improving durability. Recently, a strong interest has been oriented toward polymer modification of carbon fiber-reinforced cements.

There are no commercially available MDF cement products in the world at present because of their very poor water resistance. MDF cements using an anhydrous phenol resin precursor, which were newly developed by Maeda et al. [25], have similar high flexural strength and very high water resistance compared to conventional MDF cement. Such superior water resistance may lead to the development of commercially available MDF cement products.

Anti-washout underwater concretes are produced by the addition of polymeric anti-washout admixtures such as cellulose- or polyacrylamide-based water-soluble polymers at polymer-cement ratios of 0.2 to 2.0% during the mixing of ordinary cement concrete to chiefly improve its anti-washout ability. In recent years, as concrete structures in harbor, bridge, or marine construction have become larger in scale, the need for anti-washout underwater concretes assuring effective underwater placement has increased.

Because the rapid deterioration of reinforced concrete structures has become a serious problem in Japan, an intense interest is focused on polymer-modified mor-

TABLE 3. Recent developments in polymer-modified mortar and concrete (Part 2)

Topic	Outline
8. Antiwashout underwater concretes	Development of underwater concreting systems using cellulose- or polyacrylamide-based water-soluble polymers [30]
9. Very rapid-hardening PMM and PMC	(1) Development of shotcreting systems using magnesium acrylate, having a setting time of 1 second or less [31] (2) Development of SBR-modified ultrarapid-hardening PMM and PMC using ultrarapid-hardening cement for repair materials and overlays [32]
10. Durability of PCM	(1) Examination on carbonation [33], chloride ions (Cl^-) or oxygen (O_2) [35] diffusion behavior of PCM (2) Weatherability of PMM or PMC through long-term outdoor exposure [36]
11. Repairing systems using PMM for reinforced concrete structures [37]	(1) Development of repairing systems using PMM and corrosion inhibitors [38] (2) Development of repairing systems using PMM and alkalinity-imparting agents (3) Development of PMM permanent forms using PAE emulsion with polyethylene nets or SAE emulsion with alkali-resistant glass fiber nets [39]
12. PMM waterproofing systems	(1) Development of PMM for liquid-applied membrane waterproofing systems [40,41] (2) Development of siliceous coatings with EVA and PAE emulaions [42]
13. Artificial wood	Development of calcium silicate-SBR latex-glass fibers mixtures [43]
14. Reuse and recycling	PMM and PMC using FRP (fiber-reinforced plastics) powders manufactured from waste FRP products [44]
15. Waste encapsulation	Encapsulation of radioactive waste by EP-modified pastes [45]

tars and pastes as repair materials, and there is a growing demand for them. As mentioned above, this trend is similar to that in other advanced countries. In connection to such a trend, the carbonation, chloride ion penetration, and oxygen diffusion of polymer-modified mortars and concretes have been investigated in various countries. As a result, it is found that they have a marked resistance to carbonation, chloride ion penetration, or oxygen diffusion. They can be recommended as low-cost, promising repair materials for reinforced concrete structures.

Topics 12, 13, 14 and 15 in Table 3 are mainly concerned with environmentally-conscious developments in the field of polymer-modified mortar and concrete. In comparison with conventional membrane waterproofing systems such as asphalt membrane waterproofing systems and liquid-applied membrane waterproofing systems with organic solvents, liquid-applied membrane waterproofing systems using polymer-modified mortars or slurries are free from poisonous organic solvents or gases with disagreeable odors, and do not pollute the atmosphere. In Japan, it is very difficult to execute hot-applied asphalt membrane waterproofing systems in built-up or urban areas at present, while the polymer-modified mortar liquid-applied membrane waterproofing systems are promising for deck roof waterproofing. The developments of artificial wood and permanent forms as replacements for plywood forms are most important from the viewpoint of the preservation of forest resources, especially tropical rain forests. The effective reuse and recycling of large quantities of waste Fiber Reinforced Plastics (FRP) products from various industrial applications and the encapsulation of hazardous radioactive wastes should be sufficiently examined from the viewpoints of environmental protection and resources exploitation.

Recent Progress in Polymer Mortar and Concrete

For the 40 years or more, the development of polymer mortar and concrete has been conducted in various countries. As a result, polymer mortar and concrete became the dominant materials in the construction industry in the 1970s in Japan and Europe, and in the 1980s in the United States. Today, the polymer mortar and concrete are competitively employed as popular construction materials. In general, the polymer mortar is used for finishing work in cast-in-place applications, and the polymer concrete for precast products.

Commercially available liquid resins for polymer mortar and concrete include various thermosetting resins, tar-modified resins, and methacrylate monomers. Figure 3 illustrates the classification of liquid resins for polymer mortar and concrete. In Japan, the liquid resins for polymer mortar are chiefly epoxy resin, unsaturated polyester (UP) resin (i.e., polyester-styrene system), vinyl ester (VE) resin and methyl methacrylate (MMA) monomer, and the most common liquid resin for polymer concrete is unsaturated polyester resin. The most common types of the liquid resins in the United States and Western Europe are methyl methacrylate monomer, unsaturated polyester and epoxy resins, and MMA monomer and unsaturated polyester resin, which have the lowest cost. Furan resin (mainly furfural-acetone

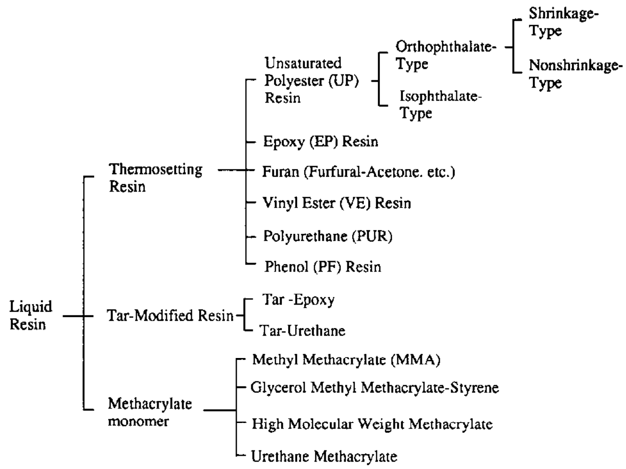

FIGURE 3. Classification of liquid resins for polymer mortar and concrete.

resin) is widely used for the same purpose in Russia and Eastern Europe. The use of the MMA monomer is limited because of its higher flammability and disagreeable odor. However, it has received much attention on account of the good workability and low-temperature curability of the polymer mortar and concrete made from it. In recent years, some trials on the application of recycled monomers or polymers to the liquid resins were done.

Tables 4 and 5 summarize recent developments in polymer mortar and concrete of the past several years. Some commentaries on the recent developments in the polymer mortar and concrete are described below.

In the structural applications of polymer mortars and concretes, mild steel bars (for conventional cement concrete), high-strength steel bars (for prestressed concrete) and FRP (fiber reinforced plastics) rods with carbon or glass fibers are used to reinforce the members with polymer mortars and concretes, and steel fibers, glass fibers, etc. are employed to reinforce polymer mortars and concretes themselves. It is most important to select the effective reinforcements corresponding to the strength of polymer mortars and concretes.

The low-temperature curability of polymethacrylate mortars and concretes is an exotic, interesting property compared to ordinary cement concrete, and enables repair work for refrigeration warehouses and construction work in the winter season or cold districts.

In general, polymer mortars and concretes are mixed using forced mixing-type batch mixers, and cast into forms or molds in a manner similar to that for conven-

TABLE 4. Recent developments in polymer mortar and concrete (Part 1)

Topic	Outline
1. New liquid resins for PM and PC binders	(1) Development of high-molecular weight methacrylate, low-odor acrylic monomer and urethane methacrylate for binders [46,47] (2) Development of low styrene emission UP resins (LSE) and low styrene-containing UP resins (LSC), i.e., high-solids resins for binders. In LSE, the styrene is completely or partially replaced with toluene or p-methyl styrene [48] (3) Development of composite or combined liquid resins for binders, consisting of UP resins and vinyl monomers [49]
2. Mix design systems for PM and PC [50]	(1) Mix design systems for UP mortar and concrete (2) Mix design systems for polymethyl methacrylate mortar and concrete (3) Development of ready-mixed UP concrete
3. Structural design considerations for PM and PC	(1) Recommended design equations for shear and flexural strengths of reinforced PM and PC [51] (2) Proposal performance criteria of reinforced PM and PC [52] (3) Strength prediction of UP concrete by applying maturity [53]
4. Reinforcement of PC and PM	(1) Fiber reinforcement of PC and PM by steel fibers or glass cloths [54] (2) Reinforcement of EP concrete by steel bars [55] (3) Development of reinforced or prestressed UP concrete with FRP rods using carbon or glass fibers [56] (4) Reinforcement of reinforced cement concrete by FRP, glass fiber-reinforced UP mortar, polymethyl methacrylate-impregnated ferrocement and highly reinforced ferrocement [57]
5. PM and PC materials modeling	(1) Materials modeling in optimization of PC [58] (2) Microstructure characterization of PC [59] (3) Creep law for PC [60]
6. Low-temperature curability of PM and PC	Low-temperature curability of polymethacrylate mortars and concretes using methyl methacrylate, urethane methyl methacrylate and glycerol methyl methacrylate-styrene at 0–25°C [61,62]
7. Long-term durability of PM and PC	(1) Long-term durability of UP or polymethyl methacrylate mortars and concretes [63] (2) 30-year experience using EP concrete in hydraulic structures [64]

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TABLE 5. Recent developments in polymer mortar and concrete (Part 2)

Topic	Outline
8. Automated application systems of PM and PC	(1) Development of small-diameter shield tunneling system using a quick-setting UP mortar [65] (2) Shotcreting systems using PM and PC [67] (3) Development of automated mixing and continuous paving trains for PC overlays [68]
9. PM and PC for underwater construction work	Development of polymethyl methacrylate mortar and concrete placed and bonded underwater [69,70]
10. Repairing systems using PM and PC for reinforced concrete structures	(1) Development of permanent forms using UP or VE concrete [71] (2) Development of repairing systems using PM and PC [72,73]
11. Precast PM and PC products	(1) Development of mass production systems using PM and PC [67] (2) Development of centrifugally cast high-strength pipes using UP mortar [74] (3) Development of projectile impact ballistic panels using UP or VE concrete [75] (4) Development of electric insulators using PC [76] (5) Development of ecologic filter pipes using PC [77]
12. Artificial marble tiles and panels	Development of artificial tiles and panels made with polymer pastes with flame-retarding fillers such as aluminum hydroxide and magnesium hydroxide [78]
13. PM and PC for machine tool structures	(1) Development of EP concrete for machine tool structures [79,80] (2) Development of polymethyl methacrylate concrete for machine tool structures [81] (3) Development of machine tool structures made by covering PMC or cement concrete with furan-epoxy concrete [82]
14. Reuse and recycling	(1) PM and PC using recycled polyester resins produced from PET bottles [83] (2) PM and PC using FRP powders manufactured from waste FRP products [84]
15. Waste encapsulation	(1) Encapsulation of geothermal waste with heavy metals by UP concrete [85] (2) Development of UP concrete products with crushed waste glass as aggregate [86]

tional cement mortar and concrete. Refined continuous mixers are also available. It is most important that the developments of mass production systems for precast polymer mortars and concretes and of automated application systems for cast-in-place polymer mortars and concretes cause a cost reduction and good cost-performance balance.

In recent years, the demand of artificial marble products has been growing. The three largest markets of artificial marble products are systematized kitchen, washstand, and systematized bath fields. In the near future, if the weather resistance of artificial marble is improved greatly, the artificial marble products will widely be used as exterior finish materials for buildings. Furthermore, if a success in the cost reduction of artificial marble products is brought down, the share of natural marble will considerably be replaced by the artificial marble. This may save a natural resource.

Topics 14 and 15 in Table 5 are chiefly related to environment-conscious developments in the field of polymer mortar and concrete. The effective reuse and recycling of large quantities of PET bottles and waste FRP products and the encapsulation of geothermal waste or crushed waste glass should also be examined from the viewpoints of environmental protection and resources exploitation. The development of permanent forms as replacements for plywood forms should be considered from the viewpoint of the preservation of forest resources as stated above. To prevent the pollution of the atmosphere due to styrene emission from UP resins, LSE and LSC are developed at present. Furthermore, some problems in the polymer mortars and concretes are the toxicity, explosibility, fire hazard, and uncomfortable odors of liquid resins, initiators and promoters for their binders, and the ecologically safe disposal of cleaning solvents for the mixers and tools used in their applications.

Recent Progress in Polymer-Impregnated Mortar and Concrete

Currently, polymer-impregnated mortar and concrete are rarely used as construction materials because of a poor balance between their performance and their high processing cost and awkwardness in applying despite their excellent performance. The precast products are manufactured filling an order at Ozawa Concrete Industries in Japan, which is the only manufacturer in the world. The main products of this company are permanent forms for improving the durability of reinforced concrete structures. The last application of polymer-

TABLE 6. Recent developments in polymer-impregnated mortar and concrete

Topic	Outline
1. Durability improvement of reinforced concrete structures by field polymer precast PIC products	(1) Development of field polymer impregnation techniques using alkyl alkoxy silanes or linseed oils for the purpose of preventing mainly chloride-induced corrosion [88–90] (2) Development of highly durable PIC permanent forms using methyl methacrylate [91]
2. Polymer impregnation of natural stone	(1) Development of field polymer impregnation systems using epoxy resins, polyurethanes, acrylic resins, silanes, perfluoropolyethers, etc. for the conservation of natural stone in cultural and historical assets [92,93] (2) Quality improvement of soft stones such as tuff, sand stone and andesite by polymer impregnation using MMA [94]

impregnated concrete in the United States was the field polymer impregnation of the roadway of the Grand Coulee Dam at a cost of US $ 51/m^2 in 1982 [87]. A recent interest has been oriented toward the improvement in durability of reinforced concrete structures by field polymer impregnation techniques using alkyl alkoxy silanes. The similar field polymer impregnation techniques are often applied to natural stone for the conservation of cultural and historical assets. Table 6 lists recent developments in polymer-impregnated mortar and concrete.

Industry Activities and Standardization Work

Of many international congresses, symposiums, and workshops on polymers in concrete or concrete-polymer composites, the International Congresses on Polymers in Concrete have been held eight times since 1975. At the Third Congress in Koriyama, Japan in 1981, the formal international organization, the International Congress on Polymers in Concrete (ICPIC) was founded to hold periodic congresses and disseminate information on concrete-polymer composites or polymers in concrete.

In Europe, the Technical Committee (TC)-105-CPC (Concrete-Polymer Composites) of the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) was active in preparing a state-of-the-art report and terminology of concrete-polymer composites. RILEM TC-113-CPT (Test Methods for Concrete-Polymer Composites) prepared 31 test methods for concrete-polymer composites, mainly polymer-modified mortar and concrete, and polymer mortar and concrete. The Federal Lander Technical Committee, Bridge and Structural Engineering of the Federal Ministry for Transport in West Germany issued four technical regulations for polymer-modified mortar and concrete, and polymer mortar and concrete as listed below.

In the United States, Committee 548 Polymers in Concrete of the American Concrete Institute (ACI) has held a symposium every two or three years, publishing the respective volumes of the proceedings. The committee has also issued a state-of-the-art report and a user's guide. In 1986, the Society of the Plastics Industries (SPI) organized the Polymer Concrete Committee, and prepared 12 test methods for polymer concrete. The American Society for Testing and Materials (ASTM), under Committee C 09 Concrete and Concrete Aggregates, has established Subcommittee C 09.03.19 Poly-

TABLE 7. National standards and governmental regulations for concrete-polymer composites in advanced countries

Type of Standard or Regulation		Type of Concrete-Polymer Composite	Designation
National Standard	JIS	PMC	JIS A 1171 ~ 1174, 6203, 6909, 6916
		PC	JIS A 1181 ~ 1186, 5350
	ASTM	PC	ASTM C 267, 307, 308, 321, 395, 399, 413, 531, 579, 580, 658, 881, 882, 884, 905 ASTM D 3262, 3517, 3840
	BS	PMC&PC	BS 6319 Part 1 ~ 12
	DIN	PC	DIN 51290
	GOST	PC	GOST 25246-82, 25991-83
Govermental Regulation	Federal Ministry for Transport Technical Regulation (Germany)	PMC	TP BE-PCC, TL BE-PCC
		PC	TP BE-PC, TL BE-PC
	CIS Guide (Russia)	PC	VSN-12-84, SN-525-80

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TABLE 8. Main institutional standards, standard specification and guides for concrete-polymer composites in advanced countries

Institution or Organization	Type of Concrete-Polymer Composite	Designation or Title
JCI (Japan)	PMC	JCI Standards for Test Methods for Polymer-Modified Mortars (1)-(17)
SPI (U.S.A.)	PC	SPI Standards: SPI Polymer Concrete Test Methods (1.0)-(7.0), (9.0)-(11.0), (13.0)-(14.0)
ACI (U.S.A.)	PMC	ACI 548.4 Standard Specification for Latex-Modified Concrete (LMC) Overlays
JSMS (Japan)	PC	Recommendation for Design of Polyester Resin Concrete Structures
		Guide for Mix Design of Polyester Resin Concrete
AIJ (Japan)	PMC, PC & PIC	Guide for the Use (or Execution) of Concrete-Polymer Composites
ACI (U.S.A.)	PMC, PC & PIC	ACI 548.1 R Guide for the Use of Polymers in Concrete
	PC	ACI 548.5 R Guide for Polymer Concrete Overlays

mer Modified Concrete, and has already published many standards on polymer mortar as described later.

In Japan, the Synthetic-Resins-for-Concrete (or Polymers-in-Concrete) Committee of the Society of Materials Science, Japan (JSMS) and the Polymers-in-Concrete Committee of the Japan Technology Transfer Association (JTTAS) are currently playing the leading role in the field of the concrete-polymer composites. The Plastics Concrete Committee of the Architectural Institute of Japan (AIJ) which had contributed to the field of the concrete-polymer composites for many years published a user's guide and a state-of-the-art report, and was discharged in 1987. The Japan Concrete Institute (JCI) issued 17 standards for test methods for polymer-modified mortars in 1987 as stated later. The Society of Materials Science, Japan (JSMS) also published a design recommendation for polyester concrete structures in 1985 and a mix design guide in 1992.

Among the countries using concrete-polymer composites, standardization work on their test methods and quality requirements has been in progress in the United States, Japan, the United Kingdom, the Soviet Union (Russia) and Germany. Table 7 lists national standards and governmental regulations for the concrete-polymer composites, which have been published up to the present time. Table 8 shows main institutional standards, standard specification, and guides for the concrete-polymer composites in advanced countries.

Conclusions

To cope with the technical innovations in the construction industry in recent years, useful polymer-modified mortar and concrete, and polymer mortar and concrete as high-performance or multifunctional construction materials have been actively developed, particularly in advanced countries. A great interest is currently focused on high-grade redispersible polymer powders, repair and durability-improving materials for reinforced concrete structures, mass production systems, automated cast-in-place application systems, artificial marble products, and machine tool structures. Field polymer impregnation techniques using silanes are widely used for durability improvement of reinforced concrete structures. Similar techniques are also applied to natural stone for the conservation of cultural and historical assets. Permanent forms using polymer-impregnated concrete are produced at a Japanese manufacturer. Concrete-polymer composites can be used for reuse, recycling, or encapsulation of waste materials from other industries, and to produce ecologically safe and energy-saving materials.

References

1. Ohama, Y. *Concrete Journal* **1990,** 28(4), 5–17.
2. ACI Committee 548 *Journal of the American Concrete Institute* **1986,** *83,* 798–829.
3. Fowler, D.W. In *Polymers in Concrete, Proceedings of the 6th International Congress on Polymers in Concrete;* Huang, Y; Wu, K.; Chen, Z., Eds.; International Academic Publishers: Beijing, 1990; pp 10–27.
4. Schneider, S.I.; DeWacher, D.R.; Palmer, J.G. In *Polymer-Modified Hydraulic-Cement Mixtures STP 1176;* Kuhlmann, L.A.; Walters, D.G., Eds.; ASTM: Philadelphia, 1993; pp 76–89.
5. Ohama, Y.; Demura, K.; Kim, W. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 81–90.
6. Ohama, Y.; Demura, K.; Satoh, Y.; Tachibana, K.; Miyazaki, Y. In *Superplasticizers and Other Chemical Admixtures in Concrete SP-119;* Malhotra, V.M.,Ed.; ACI: Detroit, 1989; pp 321–342.
7. Ohama, Y.; Demura, K.; Miyake, M. *Journal of the Society of Materials Science, Japan* **1991,** *40,* 1202–1207.
8. Ohama, Y.; Demura, K. In *Proceedings of the 7th International Conference on Mechanics and Technology of Composite Materials;* Central Laboratory of Physico-Chemical Mechanics: Sofia, 1994; pp 144–149.
9. Lay, I.; Gupta, A.P.; Biswas, M. *Cement and Concrete Composites* **1994,** *16,* 309–316.

10. Jo, Y.; Ohama, Y.; Demura, K. *Transactions of the Japan Concrete Institute* **1993,** *15,* 85–92.
11. Bonora, V.; Saccani, A.; Sandrolini, F.; Belz, G.; Dinelli, G. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 221–226.
12. Kaempfer, W. ibid.; pp 277–283.
13. Jo, Y.; Ohama, Y.; Demura, K. *Journal of Structural and Construction Engineering, Architectural Institute of Japan* **1994,** No. 464, 1–6.
14. Jo, Y.; Ohama, Y.; Demura, K. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 231–240.
15. Ye, Z. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 57–62.
16. Lin, C.C. ibid.; pp 613–618.
17. Chandra, S.; Xu, A. ibid.; pp 187–192.
18. Takeuchi, H.; Okamoto, T.; Demura, K.; Ohama, Y. *Transactions of the Japan Concrete Institute* **1991,** *13,* 17–24.
19. Sustersic, J. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 649–654.
20. Bijen, J.M. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 533–540.
21. Rols, S.; Ambroise, J.; Pera, J. ibid.; pp 403–408.
22. Soroushian, P.; Aouadi, F.; Nagi, M. *ACI Materials Journal* **1991,** *88,* 11–18.
23. Shirai, A.; Ohama, Y. In *Proceedings of the 33rd Japan Congress on Materials Research;* Society of Materials Science, Japan: Kyoto, 1990; pp 41–46.
24. Shirai, A.; Ohama, Y. In *Fiber Reinforced Concrete-Modern Developments;* Banthia, N.; Mindess, S., Eds.; The University of British Columbia: Vancouver, 1995; pp 201–212.
25. Maeda, N.; Hasegawa, M.; Kawano, T.; Kobayashi, T.; Pushpalal, G.K.D. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 131–140.
26. Pushpalal, G.K.D.; Maeda, N.; Kawano, T.; Kobayashi, T.; Hasegawa, M.; Takata, T. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 631–636.
27. Lewis, J.A.; Boyer, M.A. *Advanced Cement Based Materials* **1995,** *2,* 2–7.
28. Ohama, Y.; Demura, K.; Kobayashi, T. In *Proceedings of the 6th International Conference on Durability of Building Materials and Components;* Nagataki, S.; Nireki, T.; Tomosawa, F., Eds.; E&FN Spon: London, 1993; pp 175–183.
29. Tan, M.; Lu, J.; Wu, K. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 655–660.
30. JSCE Concrete Committee *Concrete Library of JSCE (Japan Society of Civil Engineers)* **1992,** No. 19, 1–55.
31. Amano, T.; Ohama, Y.; Takemoto, T.; Takeuchi, Y. In *Proceedings of the First Japan International SAMPE Symposium;* Igata, N.; Kimpara, I.; Kishi, T.; Nakata, E.; Okura, A.; Uryu, T., Eds.; Japan Chapter of SAMPE: Tokyo, 1989; pp 1564–1569.
32. Sekino, K. *Concrete Research and Technology* **1993,** 4(1), 103–112.
33. Ohama, Y.; Demura, K.; Miyake, M. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 331–336.
34. Nepomuceno, A.A.; Andrade, C. ibid.; pp 233–238.
35. Ohama, Y.; Demura, K.; Kobayashi, K.; Satoh, Y.; Morikawa, M. *Cement and Concrete Research* **1991,** *21,* 309–315.
36. Sprinkel, M.M. In *Polymer-Modified Hydraulic-Cement Mixtures STP 1176;* Kuhlmann, L.A.; Walters, D.G., Eds.; ASTM: Philadelphia, 1993; pp 141–154.
37. Hewlett, P.C. *Concrete International* **1993,** 15(3), 39–41.
38. Berke, N.S.; Dallaire, M.P.; Weyers, R.E.; Henry, M.; Peterson, J.E.; Prowell, B. In *Corrosion Forms and Control for Infrastructure STP 1137;* Chaker, V., Ed.; ASTM: Philadelphia, 1992; pp 300–327.
39. Kawaguchi, N.; Moriuchi, M.; Kohno, K.; Horii, K. In *JCA Proceedings of Cement & Concrete No.48;* Japan Cement Association: Tokyo, 1994; pp 802–807.
40. Volkwein, A.; Petri, R.; Springenschmid, R. *Betonwerk + Fertigteil – Technik* **1988,** 54(8), 30–36; (9), 72–78.
41. Kamimoto, H.; Wakasugi, M. In *Polymer-Modified Hydraulic-Cement Mixtures STP 1176;* Kuhlmann, L.A.; Walters, D.G., Eds.; ASTM: Philadelphia, 1993; pp 34–43.
42. Tanaka, T.; Oh, S.K.; Matsumoto, Y.; Koike, M. *Journal of Structural and Construction Engineering, Architectural Institute of Japan* **1990,** No.416, 47–56; No.422, 27–36.
43. Watanabe, T.; Tsukiyama, K.; Kawano, T. In *Proceedings of the MRS International Meeting on Advanced Materials Vol. 13-Advanced Cement and Chemically Bonded Ceramics;* Doyama, M.; Sohmiya, S.; Chang, R.P.H., Eds.; MRS: Pittsburgh, 1989; pp 115–123.
44. Ohama, Y.; Demura, K.; Kobayashi, T.; Satoh, T. *The Journal of the College of Engineering of Nihon University, Series A* **1994,** *35,* 33–40.
45. Rao, S.V.S.; Lal, K.B.; Amalraj, R.V. *Cement and Concrete Research* **1993,** *23,* 896–904.
46. Ohama, Y.; Demura, K.; Kobayashi, K.; Matsueda, H. In *Proceedings of the Third Japan International SAMPE Symposium Vol. 1;* Kishi, T.; Takeda, N.; Kagawa, Y., Eds.; Japan Chapter of SAMPE: Tokyo, 1993; 190–193.
47. Bartz, T.; Senbetta, E. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 37–42.
48. Fowler, D.W. ibid.; pp 13–19.
49. Ohama, Y.; Demura, K. *Journal of the Society Materials Science, Japan* **1994,** *43,* 997–1003.
50. Ohama, Y. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 11–23.
51. Fowler, D.W.; Rebeiz, K.S. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 331–336.
52. Kaeding, A.O.; Dikeou, J.T. ibid.; pp 345–350.
53. Yeon, K.S.; Kim, K.W.; Lee, Y.S.; Kim, K.H. In *Proceedings*

of the RILEM TC-113 International Symposium on Properties and Test Methods for Concrete-Polymer Composites; Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 81–88.
54. Ohama, Y. In *Advances in Concrete Technology (2nd Edition);* Malhotra, V.M., Ed.; Canada Centre for Mineral and Energy Technology: Ottawa, 1994; pp 753–783.
55. San Jose, J.T.; Urreta, J.I.; Prado, A.; Rz-Maribona, I.; Muguerza, A. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 375–380.
56. Fukuzawa, K.; Numao, T.; Yoshimoto, M. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 325–335.
57. Neelamegam, M.; Dattatreya, J.K.; Parameswaran, V.S. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 149–154.
58. Clifton, J.R.; Czarnecki, L.; Lukowski, P. ibid.; pp 293–298.
59. Czarnecki, L.; Garbacz, A.; Kurzydlowski, K.J. ibid.; pp 299–304.
60. Boehler, J.P.; Dietl, T.; Millien, A.; Hannawald, J.; Sasse, H.R. ibid.; pp 305–310.
61. Moriyoshi, A.; Hirano, T.; Itami, K.; Tokumitsu, K.; Takahashi, M.; Nagata, S. *Sekiyu Gakkaishi* **1995,** 38(1), 57–61.
62. Moriyoshi, A.; Tokumitsu, K.; Hirano, T.; Ogasawara, A.; Nagata, S. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 509–514.
63. Yamasaki, T.; Idemitsu, T.; Watanabe, A.; Miyakawa, K. *Journal of the Society of Materials Science, Japan* **1991,** *40,* 1178–1184.
64. Topchiashvili, M.I. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 269–275.
65. Kondo, S.; Kuroiwa, M.; Kurahashi, W. Presented at *the International Congress on Progress and Innovation in Tunneling* in Toronto in 1989.
66. Kimura, Y.; Ohtake, S.; Kobayashi, Y. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 393–398.
67. Kreis, R. In *ICPIC Working Papers, ACI-ICPIC North American Workshop on Polymers in Concrete;* ACI: Detroit, 1991.
68. ACI Committee 548 *ACI Materials Journal* **1993,** *90,* 499–522.
69. Bhutta, M.A.R.; Ohama, Y.; Demura, K. In *Concrete 2000 Economic and Durable Construction through Excellence Vol.2;* Dhir, R.K.; Jones, M.R., Eds.; E & FN Spon: London, 1993; 1061–1070.
70. Bhutta, M.A.R.; Ohama, Y.; Demura, K. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 521–526.
71. Ono, T.; Matsuo, K.; Kishida, A.; Ono, S. In *JCA Proceedings of Cement & Concrete No. 48;* Japan Cement Association: Tokyo, 1994; pp 826–831.
72. Murray, M.A. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 169–174.
73. Ladang, C.; Van Gemert, D.; Leliaert, J.; Dereymaeker, J.; Verpoest, I.; Ivens, J. ibid.; pp 541–546.
74. Yeon, K.S.; Kim, K.W.; Kim, S.S.; Jang, T.Y. ibid.; pp 667–672.
75. Dancygier, A.N.; Puterman, M.; Goldman, F.; Yankelevsky, D.Z. ibid.; pp 497–502.
76. Gunasekaran, M. ibid.; pp 421–425.
77. Kreis, R.; Tost, R. ibid.; pp 473–481.
78. Ohama, Y. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 11–23.
79. Kreinbuhl, R. In *ICPIC Working Papers, ACI-ICPIC North American Workshop on Polymers in Concrete;* ACI: Detroit, 1991.
80. Tanabe, I. *JSME International Journal, Series C* **1993,** *36,* 494–498.
81. Koblischek, P.J. In *Polymers in Concrete, Proceedings of the 8th International Congress on Polymers in Concrete;* Van Gemert, D., Ed.; Technological Institute of the Royal Flemish Society of Engineers: Antwerp, 1995; pp 441–447.
82. Brailovsky, M.I.; Paturoev, V.V.; Solovjov, G.K. ibid.; pp 411–419.
83. Kitamura, T. In *Proceedings of the 49th Annual Conference of the Composite Institute of the Society of the Plastics Industry;* SPI: New York, 1994; pp 1–5/Session 15-F.
84. Rebeiz, K.S.; Yang, S.; Fowler, D.W. *ACI Materials Journal* **1994,** *91,* 313–319.
85. Fowler, D.W. In *Proceedings of the First East Asia Symposium on Polymers in Concrete;* Yeon, K.S.; Choi, J.D., Eds.; Kangwon National University: Chuncheon, Korea, 1994; pp 3–9.
86. Fontana, J.J. In *ICPIC Working Papers, ACI-ICPIC North American Workshop on Polymers in Concrete;* ACI: Detroit, 1991.
87. Smoke, G.W. In *Polymer Concrete-Uses, Materials, and Properties SP-89;* Dikeou, J.T.; Fowler, D.W., Eds.; ACI: Detroit, 1985; pp 43–49.
88. Wright, J.; Shen, Z.; Rizkalla, S. *Canadian Journal of Civil Engineering* **1993,** *20,* 844–854.
89. Ohama, Y. In *Proceedings of the Fourth International Symposium on Brittle Matrix Composites;* Brandt, A.M.; Li, V.C.; Marshall, I.H., Eds.; Institute of Economic Education: Warsaw, 1994; pp 513–522.
90. Cater, P.D. In *International Symposium on Concrete Bridges in Aggressive Environments SP-151;* Weyers, R.E., Ed.; ACI: Detroit, 1994; pp 95–117.
91. Naito, T.; Matsuoka, Y.; Shindo, T.; Ozawa, M.; Tsuruta, K. *Journal of Construction Management and Engineering, Japan Society of Civil Engineers* **1991,** No. 474/VI-20, 41–45.
92. Sasse, H.R.; Honsinger, D.; Puterman, M. In *Proceedings of the First International Colloquium on Role of Chemistry in Archaeology;* Ganorkar, M.C.; Rao, N.R., Eds.; The Birla Institute of Scientific Research: Hyderabad, India, 1991; pp 87–94.
93. Sasse, H.R.; Honsinger, D.; Schwamborn, B. In *Proceedings of the International RILEM/UNESCO Congress on Conservation of Stone and Other Materials Vol. 2;* Thiel, M.J., Ed.; E & FN Spon, London, 1993; pp 705–716.
94. Sugimoto, K.; Sivakumaran, W.; Kobayashi, S. *Journal of Finishings Technology* **1993,** 1(1), 17–24.