

RECYCLING OF MARBLE WASTES - ARTIFICIAL MARBLE

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Abstract

There is an increasing demand of industrial rocks for the use as a building and facing stone in our decorative stone industrial market. In parallel, because of observing negative public opinion for marble waste material dump areas in increasing number of marble plants, a technical analysis requirement is inevitable impact on re-evaluation of marble waste materials as an industrial matter. In this paper, an analysis results on evaluating the marble waste materials as a construction and facing stone in civil industry are presented and logical and theoretical approaches on a criteria for the aim of use, physical aspects, colour, ornament and techno-mechanical properties are determined.

INTRODUCTION

The great consumption of marble in civil industry has shown that the importance of qualified marbles is definite in decorative structures. On the effect of increased marble use, the number of marble plants is rapidly increasing in the marble producing countries. Either production cycle in the field or processing the marble blocks in the plant, a large number of marble wastes are obtained and generally this waste is dumped to the beneficial fields. Enlarging the waste potentials makes an unexpected reactions based on environmental issues. Thus, as evaluating the consumption of valuable raw materials, marble wastes should be evaluated in different industrial branches in order to gain an optimum benefit. An extensive research over beneficiation marble wastes should be certainly carried out and improved technologies are definitely needed in decorative stone industry. It is significantly expected that the use of marble wastes in a wide range of industrial area will be well known practice in the world. Previous researches in this sector have shown that recycling of these wastes and their effective evaluation in civil industry are referred to practical production artificial marble stones. This approach is a relatively new point in this field.

A comprehensive programme of undrained compressive tests of specimens prepared from 16 types of Turkish marble waste materials having different chemical and physical properties were carried out in order to produce artificial marble stones for decorative purposes. The tests were conducted based on the different size fractions.

This paper describes an evaluating method for marble waste materials as mentioned above. The test procedure followed and the analysis of test results are presented. The effects of water/solid ratio, cement content, size fraction, water/cement ratio and marble type on strength, ultra velocity performance and elastic/shear properties of artificial marble stones are discussed in detail.

ARTIFICIAL MARBLE MIXTURE DESIGN

Basically, the problem of designing an artificial marble mixture consists of selecting the correct proportions of cement, marble material type, appropriate size fraction of material, and water amount. There are many properties of artificial marble that can be specified, e.g. workability, strength requirement, density, thermal characteristics, elastic deformation modulus, and shear modulus. However, the properties most usually specified for the mixture design are :

- The workability of the artificial marble,
- The strength requirement at a curing time,
- The elastic and shear characteristics by means of specifying the minimum cement content or the maximum water/cement ratio, and in some cases restricting the type of materials to be used.

The workability enables the artificial marble to be compacted into forms having any reasonable shape safely. However, the durability ensures a long life for the hardened artificial marble against compressive loading. Considering the strength requirement, artificial marble mixture proportions can be determined on the basis of two different strength specifications: *uniaxial compressive strength* and *triaxial compressive strength*. Considering the triaxial compressive strength, loading magnitude of confining pressure plays important role for determination of the correct water/cement ratio of the mixture for a required deviatoric stress ($\sigma_1 - \sigma_3$) depending on the stress state of using area [1]. However, in many researches of construction design, mixture proportions have been discussed based on uniaxial compressive strength (σ_c) requirement.

Artificial marble mixtures with binding agents can be classified by the grain size distribution of the marble type material, such as fine marble materials or coarse-fine marble wastes, particularly by its maximum size distribution, by its water content and by its workability [2]. Artificial marble mixtures, therefore, consists of the following components:

- marble type material,
- binding agents (usually ordinary Portland cement),
- water content,
- additional agents (i.e., Pulverised fuel ash, limestone, etc).

Grinding of the marble material for workable mixture needs more water content because of having relatively large surface area which requires lubrication. To make workable mixture for construction and also for producing the required strength, water content should be determined in an experimental work. In general, an optimum workable mixture can be accepted as water/solid ratio of 0.40-0.50 for very small size fractions. The optimum ratio in producing the required strength must be determined experimentally based on laboratory strength tests in engineering judgement [3]. In order to make the appropriate mixtures, marble waste material types can be basically classified into two categories:

- fine-grained waste material types,
- coarse-grained waste material types.

The same material composition may have different strength values in different size fractions. Of course, the different material types may also have different strength values at the same size distributions. To select the optimum waste material type and its size fraction, experimental study must be carried out based on compressive strength tests. The cements currently made, sometimes to special order only, can be grouped into four main categories:

- Portland cements,
- Blended Portland cements,
- Portland cements with additives,
- High alumina cements.

The first two categories are the most widely used, the last two being required mainly for special purposes. Further, high alumina cements differ completely from Portland cements both in composition and method of manufacture. The techniques for their use differ significantly in some respects from those appropriate to Portland cements. Portland cements can also be classified into six categories:

- Ordinary Portland cement,
- Rapid-hardening Portland cement,
- Ultra-rapid-hardening Portland cement,
- Sulphate-resisting Portland cement,
- Low heat Portland cement,
- White Portland cement.

In actual case, different types of cement have different water requirements to produce pastes of standard consistence. Also, different types of cement produce artificial marbles having different rates of strength development. In rapid-hardening Portland cements the chemical reaction initially proceeds at a faster rate than in Ordinary Portland cements and the effect of this activity has been shown on typical concrete developments having a water/cement ratio of 0.5 in civil engineering practices. In most cases, Ordinary Portland cement is used as binding agent for artificial marble productions. Fine grained smelter slag and Pulverised fly ash could be added if these materials show pozzolanic behaviour.

LABORATORY EQUIPMENT AND TEST PROCEDURE

Marble Waste Materials and Sample Preparation

A series of undrained compressive tests were carried out to determine the geomechanical properties of artificial marble samples obtained from different marble waste materials. The marble wastes having different physical and chemical properties and different colours were first crushed to -12mm size fraction by a primer crusher. Their chemical and mechanical properties used in analyses are given in Table 1 and Table 2, respectively. These marble types:

- | | |
|---|--|
| <input type="checkbox"/> Bordeaux Griso | <input type="checkbox"/> Rosalia |
| <input type="checkbox"/> Elazig Black | <input type="checkbox"/> Onyx |
| <input type="checkbox"/> Salome | <input type="checkbox"/> Dry Rose Dark |
| <input type="checkbox"/> Lillac | <input type="checkbox"/> Rosso Levanto |
| <input type="checkbox"/> Venus | <input type="checkbox"/> Silver White |
| <input type="checkbox"/> Beige | <input type="checkbox"/> Traverten |

Table 1. Chemical properties of marble types.

Components %									
Marble	SiO ₂	Fe ₂ O ₃	CaO	MgO	Marble	SiO ₂	Fe ₂ O ₃	CaO	MgO
Bordeaux Griso	0.56	0.57	53.3	1.42	Lillac	0.14	0.32	51.0	4.17
Rosalia	1.25	0.55	53.5	0.40	Rosso Levanto	28.4	9.70	13.8	26.25
Elazig Black	1.48	0.86	43.1	9.30	Venus	1.48	0.86	43.1	9.30
Onyx	0.20	0.32	52.3	3.25	Silver White	1.55	0.82	44.0	9.25
Salome	1.50	0.84	43.2	9.20	Beige	0.50	0.10	52.2	2.50
Dry Rose Dark	1.20	0.23	50.0	0.001	Traverten	0.26	0.32	54.6	0.30

Table 2. Mechanical properties of marble types.

Marble Type	Density gr/cm ³	Specific Gravity gr/cm ³	Compress. strength kg/cm ²	Marble Type	Density gr/cm ³	Specific Gravity gr/cm ³	Compress. Strength kg/cm ²
Bordeaux Griso	2.74	2.76	688	Lilac	2.72	2.74	1019
Rosalia	2.70	2.73	1019	Rosso Levanto	2.61	2.72	1019
Elazığ Black	2.73	2.78	889	Venus	2.72	2.79	1010
Onyx	2.73	2.75	1125	Silver White	2.70	2.71	750
Salome	2.79	2.78	1019	Beige	2.71	2.72	1115
Dry Rose Dark	2.71	2.72	1045	Traverten	2.72	2.74	570

The optimum artificial marble matrix in terms of particle size distribution and water/solid ratios (w/s) was determined using various size fractions and water/solid ratios ranging from 0.15 to 0.20 for the mixture compositions. Based on the results of these tests, it was decided to carry out undrained compressive tests to determine the elastic and shear strength properties of the following artificial marble mixtures with Ordinary Portland Cement (OPC) as the main binding agent:

- (i) 7%OPC (ii) 10%OPC (iii) 15%OPC (iv) 20%OPC,

at water/solid ratios of 0.10 and 0.35 for different marble types.

Test Procedure, Equipment and Interpretation

Suggested techniques for determining the uniaxial compressive strength and deformability of test specimen are given by the International Society for Rock Mechanics (ISRM) Commission on standardisation of Laboratory and Field Tests [1]. The essential features of the recommended procedure are given in the following.

Undrained compressive strength test is performed on cylindrical test specimens (Figure 1) by compressing or loading them to failure. Samples were individually cast in cylindrical mould, and ends were capped. The common used height-to-diameter ratio of cylindrical marble specimens is $h/d = 2.5$ to 3.0 . The specimens after casting were cured in water and tested fully saturated at 7 and 28 days of curing. Upon failure, the specimen usually fractures by axial, brittle splitting, or fails in shear, depending upon the degree of the constrains at the ends of the test specimen offered by the platens of the testing machine and the surface quality of the parallel ends of the specimen receiving the load.

For any axial stress applied to the test specimen, the axial and lateral strains are measured either by strain gauges fitted on the specimen, or by measuring displacements. These data are used for determining the Poisson's ratio. Also, the axial deformation is recorded for use in plotting stress-strain diagrams to determine the elastic properties of the specimen. Specimens should be stored, for no longer than 30 days, in such a way as to preserve the natural water content, as far as possible, and tested in that condition [1]. There should be at least five replications of each test.

The undrained compressive strength test results also render indirectly the unconfined shear strength τ_u , and the parameters ϕ and C , commonly known as the angle of internal friction and cohesion respectively, as a function of rupture angle α . Friction on the rupture surface supports a considerable amount of axial stress. Cohesion may be regarded as the tangential strength (no-load strength).

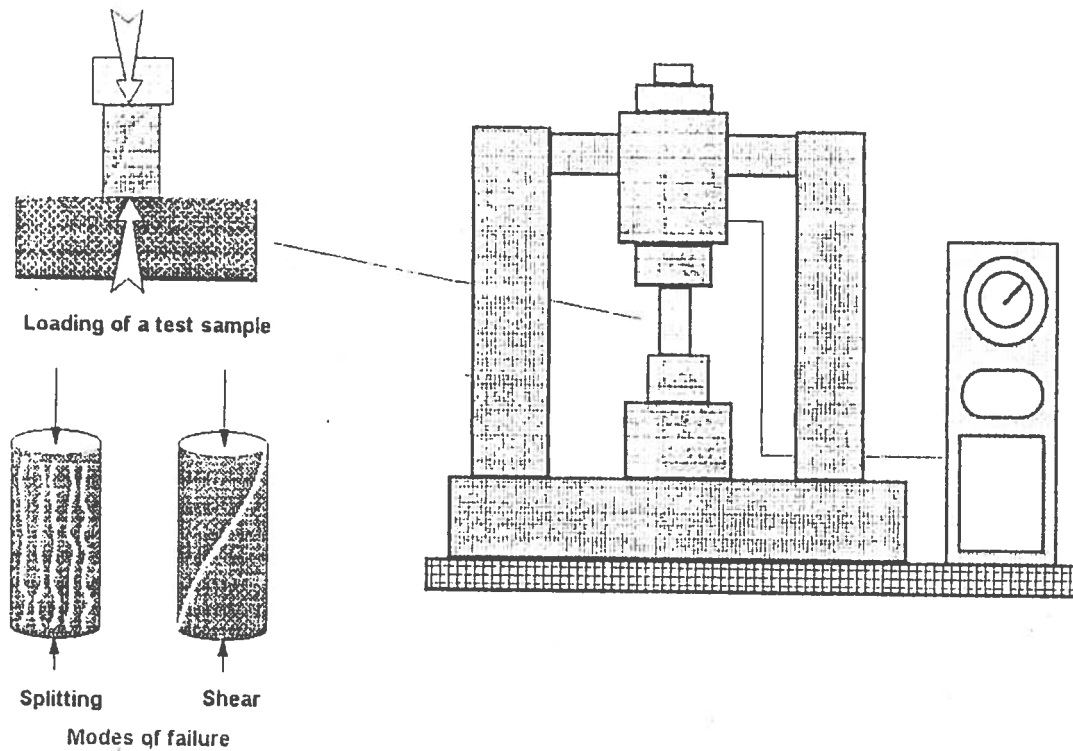


Figure 1 Test specimen and procedure for undrained compressive strength testing.

RESULTS AND DISCUSSIONS

In order to investigate the strength characteristics of artificial marble compositions, mainly axial stress (σ_c) components were evaluated for mixture combinations. For presenting the actual strength characteristics from compressive test results, axial stresses versus axial strains were plotted for mixture compositions at 7 and 28 days of curing. These curves are shown in Figure 1 for different marble waste types. Generally with increasing cement content and curing time, the strength of artificial marble composition increases. The figure also demonstrates the role of pore water pressure in terms of peak strength for different compositions. The research showed that pore water pressure gradually increases with increasing axial stress under constant value. At constant water/solid ratios, increased OPC contents result in a reduction in pore water pressure and improve the geomechanical properties of artificial marble significantly.

In accordance with the recommendation of ISRM, elastic modulus of artificial marble types were determined. It is observed that by increasing cement content and curing time, the elastic modulus of the mixture compositions increases, too. Actually, it could be said that the cemented artificial marbles are non-linear elastic material with high OPC contents and plastic material with very low OPC content. In this respect, certain allowances and intelligent choices must be made for deviations from perfect, ideal elasticity based on the engineer's personal experience thus reconciling theory with reality and rendering a rational approach to design a desired marble waste mixture. Assuming the cemented test samples are intact specimens, the uniaxial compressive strengths were determined based on Hoek and Brown failure criteria. The following relationships based on curing time, water/cement ratio and the OPC content of marble waste mixtures tested were established:

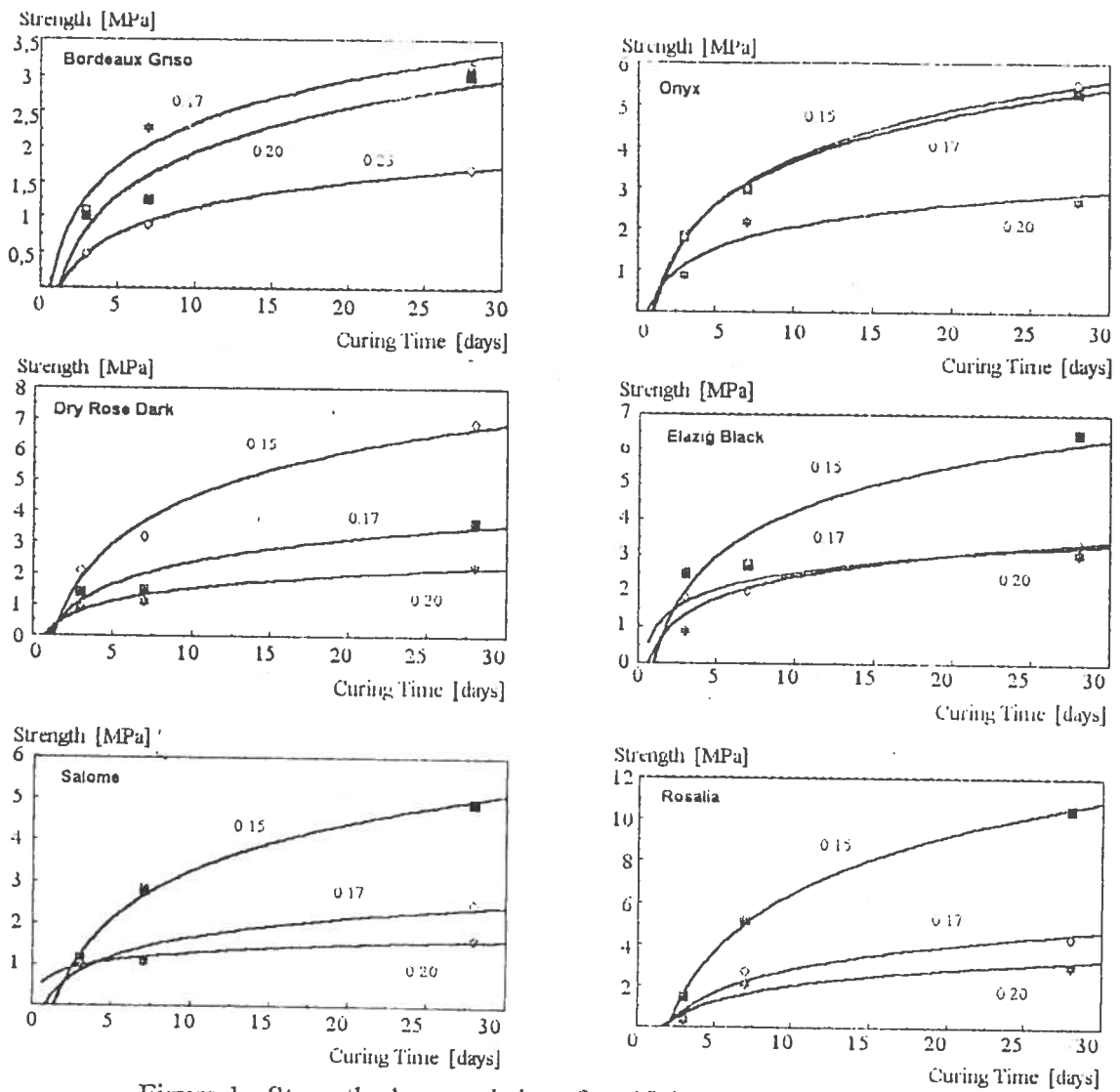


Figure 1. Strength characteristics of artificial marble compositions.

- Dry Rose Dark $\sigma_c = 19.54 + 21.41 \log T \cdot 10^{(-0.795 + 0.004 * T) W/C}$
- Salome $\sigma_c = 2.72 + 1.00 \log T \cdot 10^{(-0.624 + 0.001 * T) W/C}$
- Onyx $\sigma_c = 4.76 + 18.79 \log T \cdot 10^{(-0.585 + 0.003 * T) W/C}$
- Elazig Black $\sigma_c = 9.44 + 14.11 \log T \cdot 10^{(-0.628 + 0.002 * T) W/C}$
- Rosalia $\sigma_c = 4.38 + 24.02 \log T \cdot 10^{(-0.624 + 0.061 * T) W/C}$
- Bordeaux Griso $\sigma_c = 1.25 + 21.71 \log T \cdot 10^{(-0.551 + 0.001 * T) W/C}$

where

σ_c = Uniaxial compressive strength, MPa,
 T = Curing time, days,
 W/C = Water/Cement ratio,

It was found that the above equations could be used to predict the behaviour of artificial marble compositions prepared using marble wastes from different locations. The maximum error in the predicted values of the major principal stress at failure was found to be $\pm 5\%$ compared to the laboratory data. Current research by the authors considers the mechanical behaviour of artificial marble mixtures proposed for different countries. The predictive equations are being generalised to cover a wider spectrum of artificial marble as more data becomes available.

Seismic velocity characteristics for every type of artificial marble tested were also analysed in detail. From research findings, the strength characteristic was determined as a function of seismic velocity of the mixture compositions. Improving the seismic velocity characterisation of the mixtures, the strength also increases. This relation was tried to generalise as a comparative function using the multiple regression analysis techniques on statistical approaches. Covering a minimum error handling, this was achieved by regressing the exponential and/or polynomial relationships based on OPC content and curing time specifications. The characteristic manner for different artificial marble types were plotted in Figure 2 and the equations established are as follows:

Dry Rose Dark	● coarse -grained	$V = (1090 + 1191 \log T) 10^{(0.019 - 0.008 * \log T) \text{ OPC}}$
	● fine-grained	$V = (1202 + 765 \log T) 10^{(0.018 - 0.003 * \log T) \text{ OPC}}$
Salome	● coarse -grained	$V = (1881 + 1061 \log T) 10^{(0.011 - 0.004 * \log T) \text{ OPC}}$
	● fine-grained	$V = (1497 + 1634 \log T) 10^{(0.017 - 0.011 * \log T) \text{ OPC}}$
Onyx	● coarse -grained	$V = (1631 + 1281 \log T) 10^{(0.012 - 0.005 * \log T) \text{ OPC}}$
	● fine-grained	$V = (2002 + 854 \log T) 10^{(0.008 - 0.001 * \log T) \text{ OPC}}$
Elazig Black	● coarse -grained	$V = (1349 + 1044 \log T) 10^{0.007 \text{ OPC}}$
	● fine-grained	$V = (1411 + 964 \log T) 10^{(0.015 - 0.004 * \log T) \text{ OPC}}$
Rosalia	● coarse -grained	$V = (2045 + 255 \log T) 10^{(0.018 - 0.007 * \log T) \text{ OPC}}$
	● fine-grained	$V = (1659 + 1140 \log T) 10^{(0.016 - 0.007 * \log T) \text{ OPC}}$
Bordeaux Griso	● coarse -grained	$V = (1812 + 1157 \log T) 10^{(0.011 - 0.005 * \log T) \text{ OPC}}$
	● fine-grained	$V = (2092 + 789 \log T) 10^{(0.011 - 0.003 * \log T) \text{ OPC}}$

where

- V = Seismic Velocity, m/s,
- T = Curing time, days,
- OPC = Ordinary Portland Cement, %.

CONCLUSIONS

Laboratory testing of different mixtures of marble wastes under uniaxial compression was aimed at determining the effects of the following factors on strength characteristics of artificial marble types:

- Curing time,
- Cement content,
- Water/solid ratio,
- Particle size distribution,
- Cement type (binding agent),
- Marble type,
- Water/cement ratio.

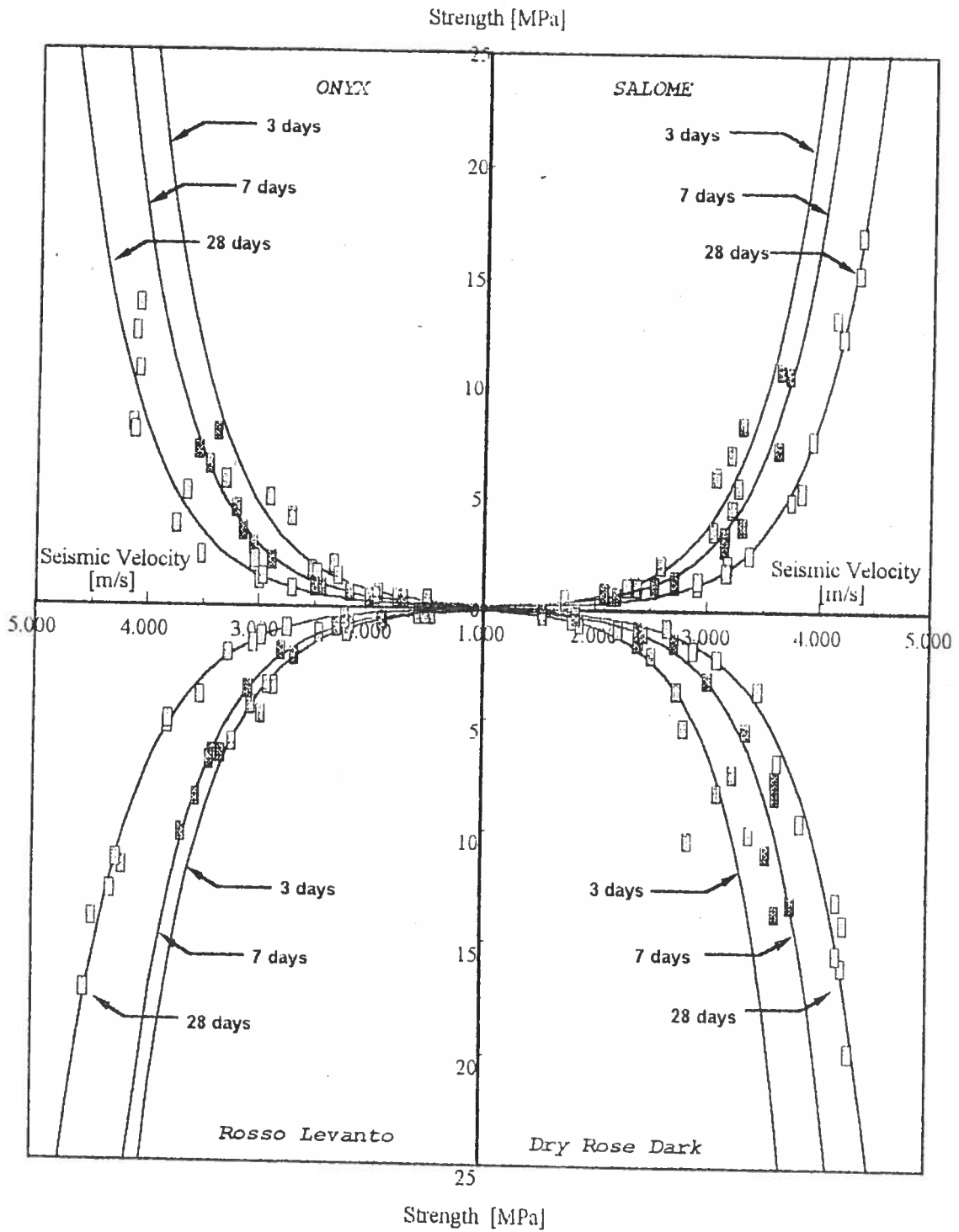


Figure 2. Seismic velocity versus strength characteristics for artificial marble compositions.

Research findings showed that 0.17-0.20 water/solid ratio is an optimum mixture component and the main binding agent for the compositions is Ordinary Portland cement. The analysis of test results led to the development of empirical relationships between the axial stresses at failure and the cement content for the marble waste mixes. It was also found that cement and

marble waste consumption in artificial marble production can be determined using the peak strength - water/cement ratio relationships developed for the mixtures tested.

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